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Daniel J. Daly
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STRATIGRAPHY AND DEPOSITIONAL ENVIRONMENTS
OF THE FOX HILLS FORMATION (UPPER CRETACEOUS),
BOWMAN COUNTY, NORTH DAKOTA

by
Daniel J. Daly

Bachelor of Arts, New Mexico Highlands University, 1974

A Thesis
Submitted to the Graduate Faculty
of the
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Science

Grand Forks, North Dakota

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This thesis submitted by Daniel J. Daly in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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This thesis meets the standards for appearance and conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

William J. Hanson 12/23/83
Dean of the Graduate School

Permission

Title Stratigraphy and Depositional Environments of the
Fox Hills Formation (Upper Cretaceous), Bowman County,
North Dakota

Department Geology

Degree Master of Science

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Date December 5, 1983

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS.	vi
ACKNOWLEDGEMENTS	xii
ABSTRACT	xiii
INTRODUCTION	1
Purpose and Scope	1
Study Area.	2
Geologic Setting.	8
Previous Work	12
Methods	45
PALEONTOLOGY	49
SEDIMENTOLOGY	52
Inorganic Sedimentary Structures.	52
Sand Petrology.	66
Inorganic Sedimentary Structure Facies.	70
STRATIGRAPHY	95
Formation Definition.	95
Member Definitions.	115
Regional Stratigraphy	130
DEPOSITIONAL ENVIRONMENTS.	143
Depositional Model	143
Environmental Interpretation of Sedimentary Structure Facies	168
Regional Environments	175

CONCLUSIONS.	181
APPENDICES	185
Appendix A. Fox Hills Outcrops, South Rim of the Williston Basin	186
Appendix B. Systematic Paleontology.	249
Appendix C. Sand Textural Data	271
REFERENCES	276

LIST OF ILLUSTRATIONS

Figure 1.	The major outcrop areas, including the study area, of the Fox Hills Formation.	2
Figure 2.	Geologic map of the study area showing the location of outcrop sites	4
Figure 3.	Stratigraphy and thickness of the Fox Hills Formation in outcrop along the south rim of the Williston Basin	10
Figure 4.	Summary, by outcrop area, of the history of investigations of the Fox Hills Formation along the south rim of the Williston Basin.	13
Figure 5.	Historical development of the Fox Hills Formation in the study area	23
Figure 6.	Stratigraphic terminology presently applied to the Fox Hills Formation in the south half of the Williston Basin	29
Figure 7.	The Timber Lake Member in the Missouri Valley of North Dakota (site 7-2)	35
Figure 8.	Sedimentary structures in the Timber Lake Member in the Missouri Valley of North Dakota (site 7-2).	35
Figure 9.	The Bullhead lithofacies of the Iron Lightning Member, at the type locale of the Iron Lightning Member south of Iron Lightning, South Dakota (site 5-1).	38
Figure 10.	The contact of the Fox Hills Formation (Colgate lithofacies of the Iron Lightning Member) and the overlying Hell Creek Formation (Crowhost Member) at the Crowghost Cemetery, Sioux County, North Dakota (site 7-1)	38

Figure 11.	The Colgate Member of the Fox Hills Formation (site 2-3) at Glendive, Montana, two kilometers east of the type locality.	42
Figure 12.	Sedimentary structures in the Colgate Member (site 2-5) near Glendive, Montana, two kilometers south of the type locality.	42
Figure 13.	Summary of the fossils observed or collected in the study area	50
Figure 14.	The characteristics of the sedimentary structure facies in the Fox Hills Formation in the study area.	53
Figure 15.	Wavy bedding	55
Figure 16.	Wavy bedding in the lower Fox Hills (hummocky-bedded facies)	55
Figure 17.	Wave ripples	58
Figure 18.	Wave ripples in hummocky bedding	58
Figure 19.	Hummocky stratification.	61
Figure 20.	Hummocky bed	61
Figure 21.	Trough cross-bedding	64
Figure 22.	Grain sand distribution in the sand portion (hummocky-bedded) and cross-bedded facies of the Fox Hills formation in the study area.	67
Figure 23.	The sand grain-size populations of the sedimentary structure facies	67
Figure 24.	Characteristics of the sedimentary structure facies of the lower Fox Hills Formation.	73
Figure 25.	Bedding in the upper massive-hummocky facies	75

Figure 26.	Hummocky component of the massive-hummocky facies.	75
Figure 27.	Characteristics of the lenticular subfacies of the lower Fox Hills Formation in the study area.	77
Figure 28.	The lenticular subfacies of the lower Fox Hills Formation.	79
Figure 29.	The upper portion of the normal-bedded subfacies of the lower Fox Hills	79
Figure 30.	Characteristics of the cross-bedded facies of the upper Fox Hills in the study area	84
Figure 31.	Sedimentary structures in the cross-bedded facies (site 4a)	87
Figure 32.	Epsilon cross-bedding (A) occurs atop trough cross-bedding in the upper Fox Hills (A-B).	87
Figure 33.	The middle third of the cross-bedded facies (site 2b)	89
Figure 34.	The basal portion of the cross-bedded facies (site 2b)	89
Figure 35.	Sedimentary structures in the cross-bedded facies (site 6e)	91
Figure 36.	Sedimentary structures in cross-bedded facies (site 6e)	91
Figure 37.	Structures in the cross-bedded facies (site 6d).	93
Figure 38.	The stratigraphy of the Fox Hills Formation in the study area	96
Figure 39.	Stratigraphic cross-section of the Fox Hills in the study area.	98
Figure 40.	The Trail City jarosite marker (TCjm).	102
Figure 41.	The Timber Lake concretion marker (TLcm)	102
Figure 42.	The Timber Lake ferruginous marker (TLfm).	104

Figure 43.	The Hell Creek marker (HCm)	104
Figure 44.	Hell Creek Formation (Little Beaver Creek Member; site 6f)	109
Figure 45.	The Fox Hills-Hell Creek contact (site 2a) . .	111
Figure 46.	The Fox Hills-Hell Creek contact (site 6d) . .	111
Figure 47.	The Fox Hills-Hell Creek contact (site 2b) . .	113
Figure 48.	The Trail City-Timber Lake contact (site 2d) .	117
Figure 49.	The lower Fox Hills Formation (site 5b)	117
Figure 50.	The Timber Lake Member (site 7b)	119
Figure 51.	Summary of petrologic characterizations of the sand portion of the Fox Hills Formation along the south rim of the Williston Basin.	121
Figure 52.	The Timber Lake and Colgate Members of the Fox Hills Formation (site 7a)	126
Figure 53.	Stratigraphy of the Fox Hills Formation in outcrop along the south rim of the Williston Basin.	131
Figure 54.	The lower Fox Hills Formation (site 1-1) near Fort Peck, Montana.	133
Figure 55.	The Trail City-Timber Lake contact (site 2-1) near Glendive, Montana	133
Figure 56.	Turbidites in the upper Trail City Member (site 2-6) south of Glendive, Montana.	135
Figure 57.	Proposed subsurface correlation of the Fox Hills Formation in Bowman County, North Dakota	141
Figure 58.	Depositional environments in the Fox Hills Formation of the study area.	144
Figure 59.	Panorama of depositional environments in the Fox Hills Formation of the study area. . .	146

Figure 60.	Cross section of the Fox Hills in the study area showing depositional environments.	148
Figure 61.	Irregular boxworks of <u>O. nodosa</u> in the normal bedded subfacies (site 2b)	155
Figure 62.	Zoned bioturbation in the lower Fox Hills (site 5a)	155
Figure 63.	Environmental distribution, burrowing habits, and trace fossil analogues for some modern burrowing shrimp.	157
Figure 64.	The bathymetric zonation of Seilacher (1967) as applied to the Fox Hills Formation in the study area	162
Figure 65.	Summary, by paleoenvironment, of the occurrence of <u>Ophiomorpha</u> in the rock record	164
Figure 66.	Depositional environments of the Fox Hills Formation in outcrop along the south rim of the Williston Basin.	176
Figure 67.	Geologic map of the north half of the study area (modified from Erdmann and Larsen 1934).	198
Figure 68.	Measured sections at site 1	205
Figure 69.	Measured sections at site 2	213
Figure 70.	Geologic map of the south half of the study area (modified from Erdmann and Larsen 1934).	215
Figure 71.	Measured sections at site 3	219
Figure 72.	Measured sections at site 4	226
Figure 73.	Measured sections at site 5	231

Figure 74.	Measured sections at site 6.	241
Figure 75.	Measured sections at site 7.	246
Figure 76.	Ethology of trace fossils from the lower Fox Hills in the study	251
Figure 77.	<u>Cosmorhape</u>	253
Figure 78.	Species identification for <u>Ophiomorpha</u> based on the pelleret lining	256
Figure 79.	The burrow lining and filling for <u>O. borneensis</u>	256
Figure 80.	Plan view of an <u>O. borneensis</u> gallery layer.	260
Figure 81.	<u>O. borneensis</u> "wagon wheel"	260
Figure 82.	Tiered mazes of <u>O. borneensis</u>	262
Figure 83.	<u>Thalassinoides</u> (?)	262

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ABSTRACT

The sedimentary structures, trace fossils, and lithology of the Upper Cretaceous Fox Hills Formation in Bowman County, North Dakota, were studied during the summer of 1979 and the spring of 1983. Twenty-three stratigraphic sections were measured and described and lithologic samples were collected for textural and mineralogical analysis. Also, the major outcrops of the formation in the Dakotas and Montana were visited.

The formation in the study area was previously defined as a 27-m-thick sandstone unit, containing three members--ascending, Trail City, Timber Lake, and Colgate--that was conformable with the underlying Pierre and overlying Hell Creek Formations. The Fox Hills, as here defined, is a tabular, upward-coarsening unit, typically 37 m thick, of a newly included 10-m-thick basal silt-clay unit and an overlying unit of muddy, subarkosic to sublithic, very fine to medium sand that represents the formation as previously defined. The conformable Pierre-Fox Hills contact marks the horizon above which: clay changes to silt-clay; mixed or interbedded strata occur; and trace fossils become plentiful. The Hell Creek-Fox Hills contact remains at the base of the lowest substantial carbonaceous bed.

The Fox Hills Formation contains three members, that correspond to three sedimentary structure facies, as follows (from the base): Trail City Member (massive-hummocky facies; 10 m thick); Timber Lake Member (hummocky bedded facies; 19-22 m); and Colgate Member (cross-

bedded facies; 6-9 m). The Trail City and Timber Lake Members (lower Fox Hills), dominated by hummocky bedding, contain a limited suite of trace fossils; two species of the trace fossil Ophiomorpha are the most abundant. The Colgate Member (upper Fox Hills), separated from the strata below by an erosional surface, contains root molds and leaves at its upper contact with the Hell Creek. The Fox Hills Formation in Bowman County differs from that in the type area in South Dakota in that hummocky bedding is plentiful, the strata are one-third as thick, body fossils are absent, and the Bullhead strata are absent.

In a model based on the storm-origin interpretation of hummocky bedding and the occurrence of trace fossils, the Fox Hills Formation represents shallow marine regressional deposits, predominately of storm origin, that were laid down in depths of less than 37 m, on a broad shelf, marginal and seaward of the advancing Hell Creek delta system. Deposition occurred: (1) steadily, from suspension fallout, on the outer shelf (Trail City Member); (2) episodically, in the wake of storms, on the inner shelf (Trail City and Timber Lake Members); and (3) continually by current-dominated shoreline or tidal (?) channel processes (Colgate Member). In contrast to the depositional conditions that existed later to the east in the type area (i.e., deep water and subsidence or sea level rise), deposition on the southwest basin rim was characterized by rapid progradation over a shallow shelf under local tectonic quiescence.

INTRODUCTION

Purpose and Scope

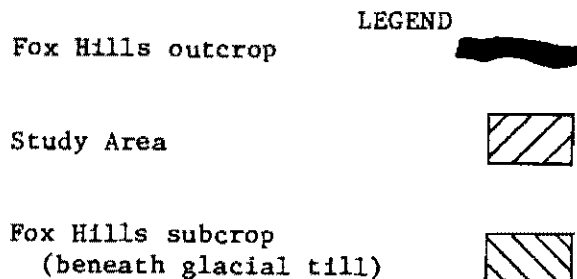
Between the valley of the Musselshell River and the area of Fort Peck in eastern Montana, and the Missouri Valley of central North and South Dakota, exposures of the Fox Hills Formation are restricted to the Cedar Creek anticline (fig. 1). On the south end of the Cedar Creek anticline, dissection of the Upper Cretaceous Pierre, Fox Hills, and Hell Creek strata by the Little Missouri and its tributaries has resulted in the occurrence of a large number of closely spaced, three dimensional, exposures. This situation is well suited for the delineation of stratigraphy and the definition of depositional regimes.

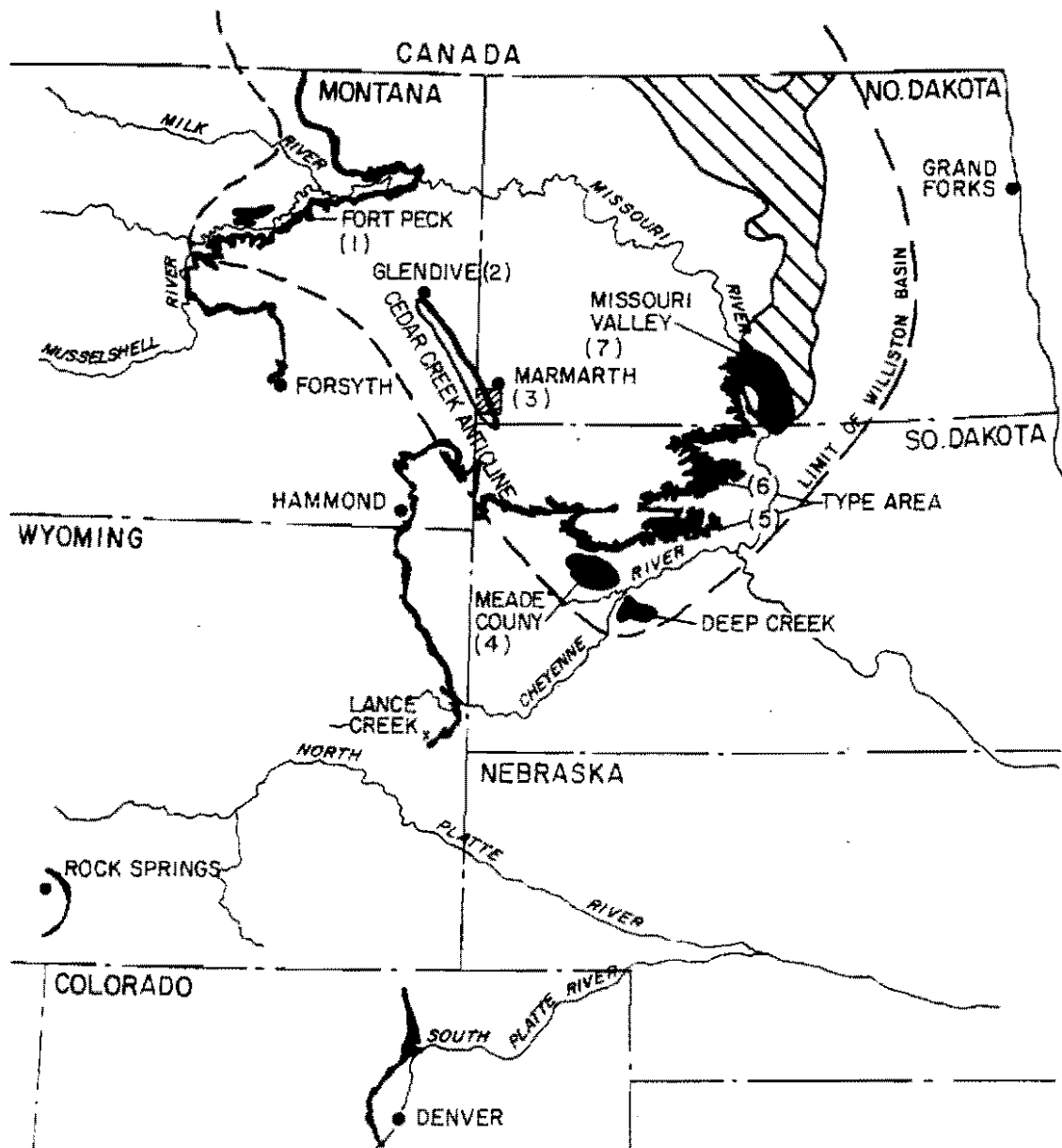
The purpose of this study is to delineate the stratigraphy, including the application of appropriate nomenclature, and to propose a depositional model for the Fox Hills Formation in southwestern North Dakota. These aims are accomplished through the evaluation of sedimentary structures, lithology, and paleontology at exposures within the study area. These results are then applied to outcrops outside the study area to create a regional picture of stratigraphy and depositional conditions.

Study Area

The area of study occurs in Townships 129 N.-113 N. and Ranges 104 N.-107 W. in westernmost Bowman County, southwesternmost North Dakota (fig. 2). The towns of Marmarth and Rhame lie to the north

Figure 1. The major outcrop areas, including the study area, of the Fox Hills Formation (modified from: Dobbin and Reeside 1929, fig. 1; Groenewold et al. 1979, fig. 2.3.1-1, 4.7.1-1). Outcrops along the south rim of the Williston Basin are divided into those on the southwest rim (loc. 1-4) and those on the southeast rim (loc. 5-7). Appendix A (part 1) provides locations and brief descriptions for the outcrops along the south rim of the Williston Basin that were visited during this study; measured sections from the study area are provided in part 2. Outcrops are designated by number on later figures and in the text. Outcrop designations for the study area (loc. 3) are given without the numerical location prefix (i.e., 1a not 3-1a), but prefixes are used for outcrops outside of the study area. The outcrops at Rock Springs were investigated by Land (1972); the outcrops in the Denver area were reported on by Dorf (1942) and Lovering et al. (1932).





0 100 Km.
0 100 mi.

N

Figure 2. Geologic map of the study area showing the location of outcrop sites (modified from: Dobbin and Larsen 1934). Appendix A (part 2) provides an explanation of the site designations and descriptions for the measured sections. The numerical location prefix "3" is omitted for the study area sections.

LEGEND

Hell Creek Formation



Fox Hills Formation

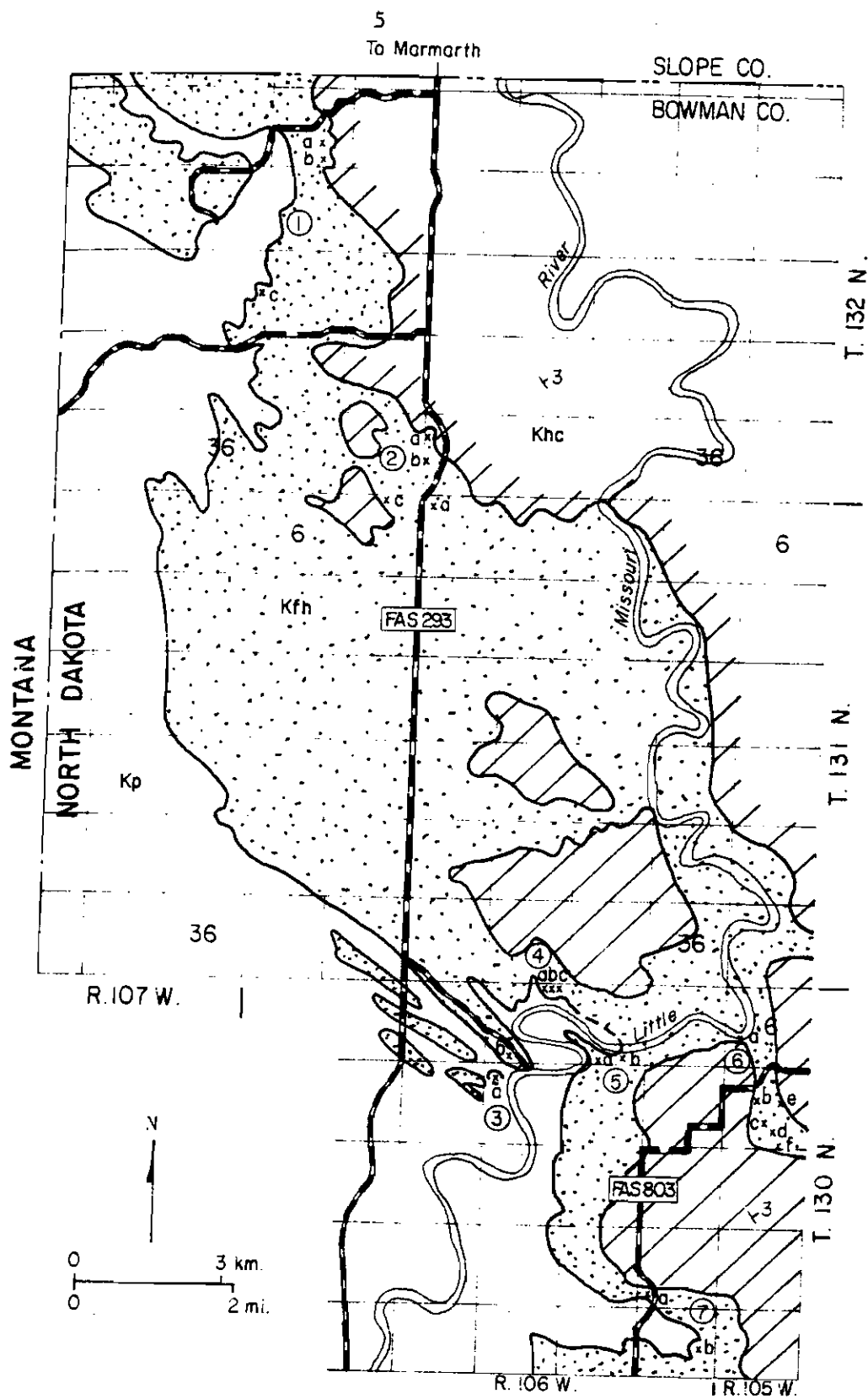


Pierre Formation



Outcrop Site in the Study Area

Number	Name	Described Section
1	Little Beaver Creek	a, b, c
2	North Creek	a, b, c, d
3	Turbiville	a, b
4	S-curve North	a, b, c
5	S-curve West	a, b
6	Horse Creek	a, b, c, d, e, f
7	Sevenmile Creek	a, b



and northeast on U.S. Highway 12. Two gravel county roads, FAS 239 south from Marmarth and FAS 803 south from Rhame, furnish the only means of ready access to the area. The region is dissected by the north-flowing Little Missouri River, bridged by U.S. 12 at Marmarth.

The area lies within the unglaciated Missouri Plateau portion of the Great Plains Physiographic Province. The relief in the area is 10-60 m.

The topography on the Pierre Formation is gently rolling with dendritic drainage, whereas the Hell Creek Formation forms badlands or steeply hilly terrain. Where not capped by the Hell Creek Formation, the topography on the Fox Hills varies from broad, flat benches to gently rolling, often with poorly defined drainage. Exposures of the complete thickness of the Fox Hills Formation are rare.

Geologic Setting

Structural setting

The Williston Basin, active at least since the Cambrian, is the dominant structural feature in North Dakota (Carlson and Anderson 1965). The basin extends into northwestern South Dakota, eastern Montana, southeastern Saskatchewan, and southwestern Manitoba (fig. 1). Two major structural lows occur in the basin, both in North Dakota (Gerhard et al. 1982): one in the vicinity of Williston and the other on the Dunn-Mercer County line. Two major structural highs occur in the basin, both in North Dakota (Gerhard et al. 1982): the north-trending Nesson anticline in Mountrail, Burke, and Williams Counties, and the Cedar Creek anticline, that

extends from western Bowman County northeast to Glendive, Montana. Normal dips into the basin average 2-4 m/km.

The Cedar Creek anticline controls the outcrop pattern in the thesis area (fig. 2). The anticline (Erdmann and Larsen 1934; Taylor 1965): (1) trends N. 30 W. and plunges to the northwest; (2) has steeper dips on the west flank ($4-33^{\circ}$) than on the gentle eastern flank (3°); (3) has a surface trace of 180 km from northeastern South Dakota to Glendive, Montana; (4) and reveals the Upper Cretaceous Pierre Shale, Fox Hills, and Hell Creek Formations in a 10-18-km-wide outcrop band.

According to Thomas (1974), the Cedar Creek anticline is an intra-block drag fold formed atop the northwest-trending Milk River basement block. Compressional forces associated with the Laramide Orogeny produced differential shear causing coupling across the block that eventually led to folding and faulting. This process was repeated throughout the Laramide foreland. After initial folding the anticline underwent a 20° rotation to the west as evidenced by a high angle reverse fault at depth on the western flank. This rotation is part of the same event that resulted in the formation of the Plevna, Westmore, and Medicine Rocks anticlines in eastern Montana.

According to Taylor (1965, p. 6), the anticline was active in Middle Tertiary time. In the Glendive area, Butler (1980) suggested that deposition on the north end was continuous during Late Cretaceous time (Pierre through Hell Creek). On the basis of extensive surface mapping and geophysical work, Clement (1983) stated that no major

uplift occurred on the anticline prior to the Oligocene.

Stratigraphic setting

The Fox Hills Formation conformably overlies the Pierre Shale with a gradational contact and conformably or locally unconformably underlies the Hell Creek Formation. The Pierre and Fox Hills Formation comprise the Upper Cretaceous Montana Group (Eldridge 1889, p. 313). Gill and Cobban (1973, p. 12) suggested that the Hell Creek also be included in the Montana Group. Collectively, these formations represent deep basin, marginal marine (Fox Hills) and fluvial deposits laid down during the final withdrawal of the Cretaceous sea from the Western Interior. The lignite bearing Fort Union Group (Tertiary) lies above.

Although the age of the Fox Hills has generally been regarded as Maestrichtian (latest Cretaceous) (Cobban and Reeside 1952), the exact time interval within that period has been cause for debate. Jeletzky (1962, p. 1006) suggested that the formation contained both early and late Maestrichtian fossils but Waage (1968, p. 139-146) reported that no evidence could be found to narrow the age beyond Maestrichtian. Gill and Cobban (1973, p. 3) considered the formation to be early Maestrichtian.

The Fox Hills Formation is time transgressive (Waage 1961, 1968; Gill and Cobban 1973), younger to the east. Using ammonites, indexed with potassium-argon-dated bentonites, Gill and Cobban (1973, fig. 18, 19) demonstrated that the formation was deposited in North Dakota and eastern Montana 70.5-68.5 million years ago.

Fox Hills correlatives for the Western Interior include: the Lenape and Horseshoe Formations in Montana (Gill and Cobban 1973, p. 20), the Dad Sandstone Member of the Lewis Shale in Wyoming (Gill and Cobban 1973, p. 20); the Lion Canyon Sandstone Member of the Williams Fork Formation (McGookey et al. 1972, p. 50); the Trinidad Sandstone in Colorado (McGookey et al. 1972, fig. 50); and the Boissevain Formation in southern Manitoba (Williams and Burk 1966, p. 169, 174-5).

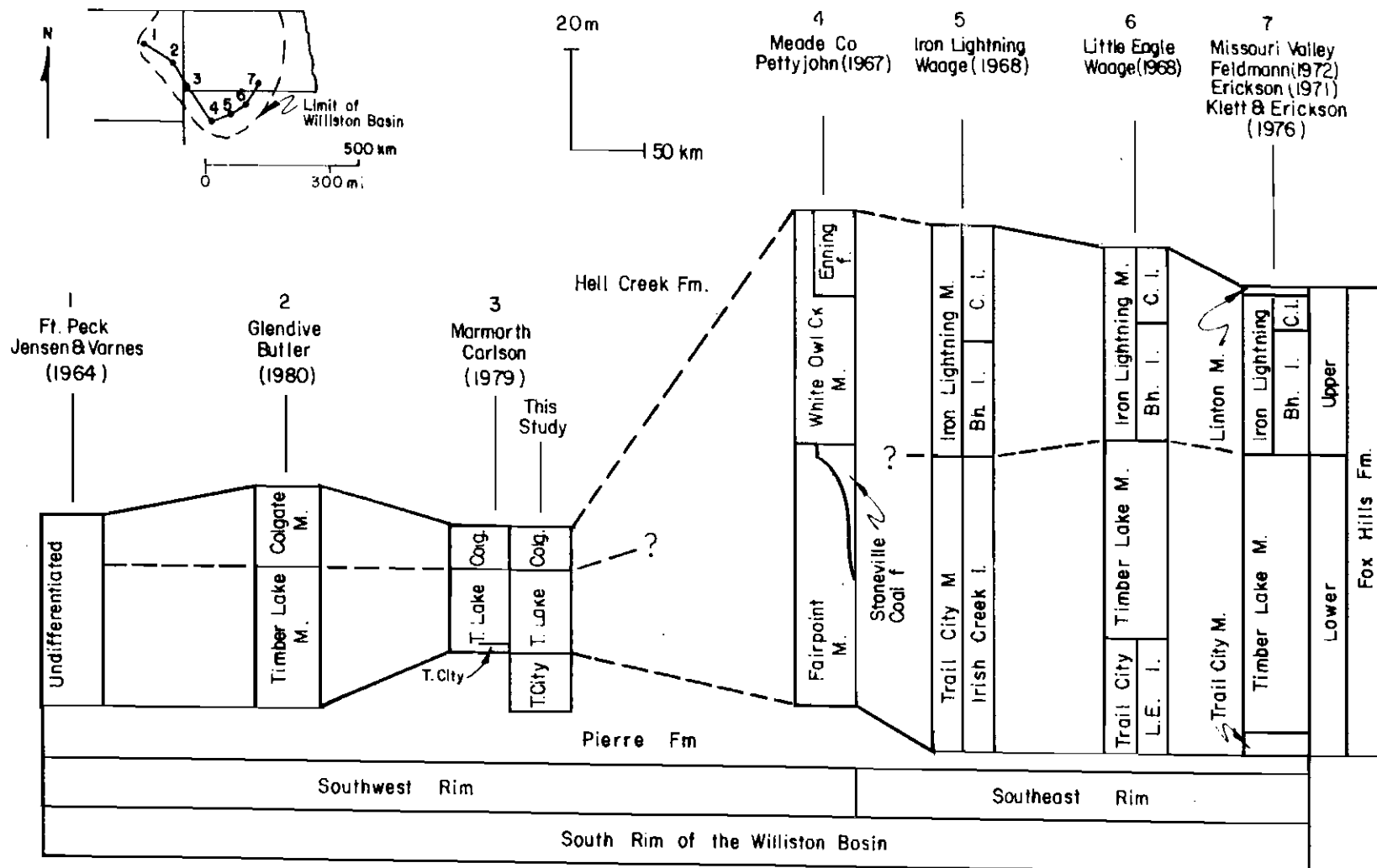
Distribution and thickness

The Fox Hills Formation is present in the subsurface throughout the Williston Basin, and crops out along the Basin rim in central North Dakota, northwestern South Dakota, and east-central Montana (fig. 1). In North Dakota, the northern two thirds of the outcrop band lies beneath glacial till.

Exposures of the Fox Hills occur along the southwest rim of the Basin at (fig. 1, 3): Fort Peck, on the Missouri River northwest of the Cedar Creek anticline (loc. 1); Glendive, on the north end of the anticline (loc. 2); Marmarth (study area), at the south end of the anticline (loc. 3); and Meade County, South Dakota (loc. 4).

Exposures of the Fox Hills on the southeast rim of the Williston Basin occur in (fig. 1, 3): Corson, Dewey and Ziebach Counties (Fox Hills type area) in north-central South Dakota (loc. 5, 6). and Sioux, Emmons, and Morton Counties (Missouri Valley of North Dakota) in south-central North Dakota (loc. 7). The Fox Hills increases in thickness from 30-45 m on the southwest rim to more than 100 m in the outcrops of the southeast rim.

Figure 3. Stratigraphy and thickness of the Fox Hills Formation in outcrop along the south rim of the Williston Basin. The unit is time transgressive to the east and outcrops on the southeast rim of the Basin are greater in thickness than those on the southwest rim. In addition, the outcrops on the southeast rim contain a rich fossil marine fauna, including ammonites, that is absent in the west. The Stoneville Coal facies (loc. 4) has no reported counterpart in outcrop elsewhere. The Bullhead lithofacies, an important component of the upper Fox Hills on the southeast rim, is absent in the western exposures.



Outside of the Williston Basin, outcrops occur in Montana along the Musselshell River, south to Forsythe (Jensen and Varnes 1964; Dobbin and Reeside 1929), and in the vicinity of Hammond (Bergantino 1980). A thick section occurs west of the Black Hills at Lance Creek, Wyoming (Dobbin and Reeside 1929, p. 19-20). A 50-140-m-thick section, composed of a repetitive 30-40-m-thick sequence, occurs in the southwest corner of Wyoming at Rock Springs (Land 1972; Asquith 1970; Harms et al. 1965). In addition, a 145-m-thick section occurs in northeastern Colorado (Dorf 1942; Lovering et al. 1932).

Previous Work

Background

Four broad periods of investigation can be recognized in the historical development of the formation. These periods, with highlights, are (fig. 4): 1853-1876, when Meek and Hayden originally defined the Fox Hills; 1900-1935, when the formation contacts were redefined and standardized by the U.S. Geological Survey; 1942-1961, when the internal stratigraphy of the formation was delineated by the Geological Surveys of North and South Dakota; and 1961-present, when a general reassessment of the formation was made by Waage.

The Fox Hills Formation in western Bowman County was investigated during 1906-1934 and since 1967. However, a detailed report solely on the Fox Hills was not produced. During the early part of the century, work on the formation occurred as a minor part of either U.S. Geological Survey lignite survey reports that were more concerned with overlying coal-bearing strata (Leonard 1906, 1908; Calvert 1912; Winchester et al. 1916; Hares 1928), or with the

Figure 4. Summary, by outcrop area, of the history of investigations of the Fox Hills Formation along the south rim of the Williston Basin.

SOUTHWEST RIM	SOUTHEAST RIM	
	MISSOURI VALLEY, N.D.	TYPE AREA, S.D.
WILDE (1983)	CARLSON (1982)	
BUTLER (1980)		
CARLSON (1979)		1980
←	CVANCARA (1976) →	
BISHOP (1973)	KLETT & ERICKSON (1976)	
←	FELDMANN (1972) →	
←	ERICKSON (1971)	1970
←	FELDMANN (1967) →	WAAGE (1968)
PETTYJOHN (1967)		
JENSEN & VARNES (1964)		WAAGE (1961)
		1960
		STEVENSON (1956)
		CURTISS (1952)
JENSEN (1951)	FISHER (1952)	1950
		MORGAN & PETSCH (1945)
	LAIRD & MITCHELL (1942)	1940
BROWN (1939)		
COLLIER & KNECHTEL (1939)		
DOBBIN & LARSEN (1934)		
ERDMANN & LARSEN (1934)		
←	DOBBIN & REESIDE (1929)	SEARIGHT (1934)
HARES (1928)		1930
THOM & DOBBIN (1924)		
		1920
WINCHESTER ET. AL. (1916)		
CALVERT (1912)	LEONARD (1912)	CALVERT ET AL. (1914)
←	LEONARD (1911)	
←	STANTON (1910)	1910
LEONARD (1908)		TODD (1910)
LEONARD (1906)		
		1900
		MEEK & HAYDEN (1856 - 1876)

"Cretaceous Boundary" problem (Stanton 1910; Calvert 1912; Thom and Dobbin 1924; Dobbin and Reeside 1929). Descriptions of the Fox Hills from this area have been included in recent reports whose major objectives were: the description of the bivalves of the Fox Hills in the Missouri Valley of North Dakota (Feldmann 1967, 1972), a report on the geology of Bowman and Adams Counties in North Dakota (Carlson 1979), and delineation of the stratigraphy and depositional environments of the Hell Creek Formation in the vicinity of Glendive, Montana (Butler 1980). A report on the stratigraphy of the Fox Hills Formation along the northern half of the Cedar Creek anticline is in preparation (Wilde 1983).

Waage (1968) and Feldmann (1967; 1972) furnished detailed accounts of the development of member terminology and contact definitions for the Fox Hills Formation. Waage was especially helpful in summarizing the pioneer work of Meek and Hayden. Klett and Erickson (1976) provided a concise summary of the evolution of member terminology. Both Brown (1962) and Frye (1969) documented the development and resolution of the "Cretaceous Boundary" or "Laramie" problem that often involved the upper contact of the Fox Hills.

Chronological Development

In 1861, Meek and Hayden (in Feldmann 1972, p. 7-9) named the Fox Hills (Formation 5 in their earlier publications) for an unspecified thickness of "gray, ferruginous and yellowish sandstone and arenaceous clays" (p. 427), that cropped out along the Cheyenne-Moreau divide in north-central South Dakota. The formation was considered uppermost Cretaceous and lay between the Pierre Formation

(formerly Formation 4) and the Tertiary Great Lignite Group. The conformable Pierre-Fox Hills contact was placed in a transitional interval in which the clay of the Pierre changed to the sandy clays of the basal Fox Hills. An extensive fossil fauna, including ammonites, proved a marine origin for the sediment. The upper contact was chosen at the base of Bed Q, a brackish water sand (base of the Colgate lithofacies according to Waage 1968; base of the Linton Member according to Klett and Erickson 1976) believed by Meek and Hayden to be the highest extent of marine strata.

During 1868-1889, enmity between the Sioux and the U. S. Government precluded scientific inquiry in the Dakota Territory. After North and South Dakota attained statehood in 1889, the infant state geological surveys became involved in geologic mapping and resource inventory. This effort was soon overshadowed by a series of lignite surveys conducted by the U. S. Geological Survey. Although this work focused on the lignite-bearing Fort Union Group, descriptions of the exposed column included the Fox Hills and Pierre Formations.

During 1900-1934: the Pierre-Fox Hills contact in the type area was placed at the base of the first sand, thereby excluding the silty, transitional lithology (Stanton 1910); the presence of an unconformity at the top of the Fox Hills or between the Pierre Shale and the Hell Creek Formation was advocated (Leonard 1906, 1908, 1911, 1912; Calvert 1912) and refuted (Stanton 1910, Winchester et al. 1916; Thom and Dobbin 1924; Hares 1928; Dobbin and Reeside 1929); the Colgate Member, originally defined as the basal 53 m of the Lance Formation in the Glendive area (Calvert 1912), was redefined and

restricted to the 12-m-thick capping sand of the Fox Hills (Thom and Dobbin 1924); and, in the type area, the upper contact was placed at the base of the first carbonaceous layer in the section (Calvert et al. 1914).

From 1933 to the late 1960s, the outcrops in southwestern North Dakota were neglected as scientific inquiry shifted to the Missouri Valley, and the work load to the North and South Dakota Geological Surveys. Through county reports in North Dakota and a combination of county reports and geological quadrangle maps in South Dakota, the delineation of local stratigraphic relationships led to the definition of members in the Fox Hills Formation.

During 1942-1967: the Colgate Member was introduced to the Missouri Valley of North Dakota (Laird and Mitchell 1942) and defined in South Dakota (Curtiss 1952); the Pierre-Fox Hills contact was redefined in South Dakota so as to include the basal silty transitional lithology in the Fox Hills as the newly defined Trail City Member, and an overlying sand member, the Timber Lake, was also defined (Morgan and Petsch 1945); the new definition of the contact and new members were applied in the Missouri Valley of North Dakota (Fisher 1952); the "banded beds" of the type area were formalized as the Bullhead Member (Stevenson 1956) in South Dakota and applied in North Dakota (Feldmann 1967); two additional members, Fairpoint and the overlying White Owl Creek, were defined for the Fox Hills section in Meade County, South Dakota (Pettyjohn 1967); and the Timber Lake Member was applied in Bowman County (Feldmann 1967).

By the late 1950s, a complete member terminology had evolved in the type area through the efforts of the South Dakota Geological Survey.

During the present period of investigation: the type area was expanded (Waage 1961); the Pierre-Fox Hills contact was redefined in the type area as the horizon marking the change from shale to silt (Waage 1961); the type area member terminology was revised with the introduction of "lithofacies" (Waage 1968) and applied in North Dakota (Erickson 1971; Cvanara 1976); the Linton Member was defined in the Missouri Valley of North Dakota (Klett and Erickson 1976); the members were identified in the subsurface between the Cedar Creek Anticline and the Missouri Valley, and the Trail City Member was tentatively applied in western Bowman County exposures (Carlson 1979); and the Timber Lake Member was applied in the area of Glendive, Montana (Butler 1980).

Definition of formation contacts

Type area.--In 1861, Meek and Hayden named the Fox Hills, a unit consisting of marine sands and sandy clays, for exposures along Fox Ridge on the Cheyenne Moreau divide in north-central South Dakota. The formation was designated Upper Cretaceous, being gradational below with the marine Pierre Formation and above with the terrestrial Great Lignite Group (including the present day Hell Creek Formation), considered to be Tertiary by Meek and Hayden.

The Pierre-Fox Hills contact was chosen on the basis of a lithologic change (shale to coarser sediment up section) with much of the transitional strata being included in the Fox Hills. Today, the specific original placement of the contact is not known for

certain; Meek and Hayden described the transition as follows (Meek and Hayden 1861, p. 427 in Waage 1968, p. 27):

This formation, Fox Hills, is generally more arenaceous than the Fort Pierre group, and also differs in presenting a more yellowish or ferruginous tinge. Towards the base it consists of sandy clays, but as we ascend to the higher beds, we find arenaceous matter increasing, so that at some places the whole passes into a sandstone. It is not separated by any strongly defined line of demarcation from the formation below, the change from fine clays of the latter to the more sandy material above, being usually very gradual.

The upper contact was placed at the base of Bed Q, an indurated sandstone believed by Meek and Hayden to be a fresh water deposit. For Meek and Hayden Bed Q denoted a change from marine to terrestrial conditions and, therefore, the close of the Cretaceous. These formation contacts were supported by the work of Todd (1910).

Stanton (1910) collected marine fossils from Bed Q, thereby casting doubt on the biostratigraphic criterion for the upper contact. Calvert et al. (1914) included Bed Q in the Fox Hills and stated (p. 18):

In general the lowermost bed of lignite or carbonaceous shale was taken as the base of the Lance [Hell Creek] formation.

This criterion, reiterated in North Dakota by Laird and Mitchell (1942), is used today as the most convenient method for separating marine from nonmarine deposition in the section. Waage (1968) commented that the local interfingering of the Fox Hills and Hell Creek (p. 119):

... make difficult the consistent use of even an arbitrary contact and also serve to underline the obvious but frequently ignored fact that the genetic change from Fox Hills environments of deposition is not everywhere expressed in the stratigraphic sequence as a single, obvious lithologic contact.

The definition of the lower contact, however, has offered fewer grounds for consensus. Stanton (1910) conceived of the Fox Hills as a sandstone and placed the lower contact at the base of the first sand thereby relegating the transition beds to the top of the Pierre. Waage (1968) offered these observations on this "Rocky Mountain" definition (p. 36):

The lithogenic equivalents of the Fox Hills Formation were observed flanking the ranges and lesser uplifts in much of the northern interior region, and the name Fox Hills Sandstone was commonly applied to them in parts of Colorado, Wyoming, and Montana. Substitution of the word "sandstone" for "formation" in these areas involved a change in the interpretation of the formation; the sandy clays transitional with the underlying Pierre Shale were included with the Pierre, and the Fox Hills contact became the base of the first sandstone in the sequence. Probably the chief reason for this change was that the base of the sandstone furnished an obvious topography break that facilitated mapping.

In the Missouri Valley the sediment is unconsolidated and the "obvious topographic break" occurs lower in the section near the base of the transitional clayey silt.

Morgan and Petsch (1945, p. 10) placed the contact 15-28 m below Stanton's (1910) horizon, where gray silty shale containing zones of "bentonite" (actually jarosite) changed upward to buff, sandy shale containing three to five zones of fossiliferous concretions. In

this gradational zone they chose the contact arbitrarily, locating it between the highest bentonite (jarosite) and the lowest zone of concretions, thereby including all fossiliferous concretions in the Fox Hills.

Waage (1961, p. 232; 1968, p. 57-58, 60-61) placed the contact below that of Morgan and Petsch (1945) at the obvious increase in silt in the section. Although the silt is often impregnated with jarosite, it is the increased silt content and not the presence of jarosite that determines the placement of the contact. Waage (1968, p. 60-61) defended his choice of contact in the following way:

... the base of the clay silt marks a change from uniformity of deposition over a wide area (characteristic offshore marine deposits) to diversity of deposition within limited areas (characteristics of marginal marine environments). The contact at the base of the silt has validity both as a lithologic and lithogenetic boundary.

Missouri Valley of North Dakota.--In exposures along the Cannonball River, in Sioux and Morton Counties, Leonard (1911) placed the upper contact of the Fox Hills at the base of a substantial sand in the middle of the modern Bullhead lithofacies. Laird and Mitchell (1942) placed the contact higher in the section at the base of the first lignitic zone.

Fisher (1952), following the work of Morgan and Petsch (1945), included transitional lithology in the base of the formation by placing the lower contact at the top of the highest jarosite zone. If a concretion zone occurred near this horizon, the contact was placed at the top of that zone. Feldmann (1967; 1972), following the work of Waage (1961; 1968), placed the contact lower in the

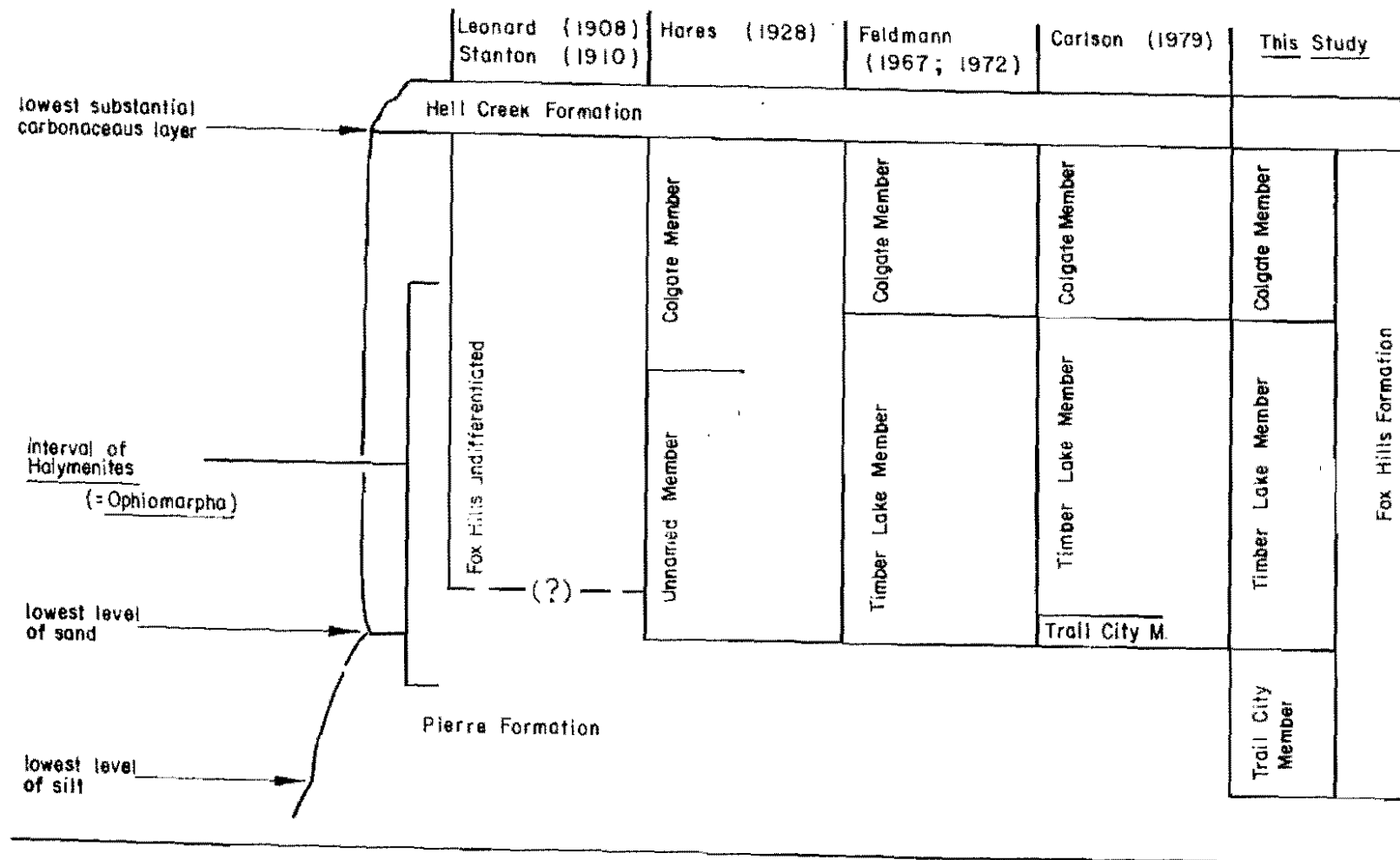
section at the base of the lowest stringers or layers of jarosite, above which the sediment abruptly becomes sandy. This choice, which included the lowest of the fossiliferous concretion zones in the Fox Hills, remains in use today.

Cedar Creek Anticline.--Leonard (1908) tentatively designated 24 m of unfossiliferous strata exposed along Little Beaver Creek (western Bowman County, Little Beaver Creek sites 1a, 1b; figs. 2, 5) as the Fox Hills Formation based on its similarity in stratigraphic position and appearance to Fox Hills outcrops in the vicinity of Hell Creek, 60 km west of Fort Peck, Montana. From the base, the section (modified from Leonard 1908, p. 44) was as follows: clay, sandy, finely laminated (6-8 m); sandstone ledge, yellow (3 m); and sandstone, light greenish gray, massive (15 m). The Pierre-Fox contact is below the creek level at this location and Leonard gave no account of it. He stated that the Fox Hills beds (p. 44):

... differ from the Pierre on which they rest in color, in consisting largely of sand, in their lamination, and absence of jointing. They are separated from the overlying strata by an unconformity.

Stanton (1910) described the Pierre through Hell Creek section on Little Beaver Creek 9 km southwest of Marmarth (Stanton gave no specific location but according to Hares 1928, the location was Sec. 7, T. 132 N., R. 106 W.; sites 1a, 1b; figs. 2, 5). He did not describe the lower contact but remarked as follows (p. 182):

Figure 5. Historical development of the Fox Hills Formation in the study area. Neither Leonard (1908) nor Stanton (1910) described the Pierre-Fox Hills contact in the study area; Stanton (1910) introduced the "Rocky Mountain" definition (basal contact at the basal sand) to the region. Hares (1928), using the "white" color as the major criterion, introduced the Colgate to the study area; Feldmann (1967; 1972) introduced the Timber Lake and Carlson (1979) suggested the presence of the Trail City Member. As of this writing, this is the only area in the region where the lower contact is chosen at the lowest sand; I have placed the contact 10 m lower in the section at the level of the lowest silt in accordance with the accepted practice elsewhere. The newly incorporated strata are assigned to the Trail City Member.



Immediately above the Pierre-Shale is a banded shale with a thickness of about 40 feet overlain by 40 feet of soft massive sandstone, yellow with iron stained bands and concretions below, grading up into gray sandstone above. This sandstone yielded a few marine fossils, including Leda (Yoldia) evansi, Tellina scitula, Entalis (?) paupercula, and Halymenites major, which confirm Leonard's reference of the sandstone to the Fox Hills.

Stanton examined the upper contact and the lower Hell Creek section at unspecified outcrops (including site 1) along Little Beaver Creek north toward Marmarth. He noted that although the change from marine to fresh water conditions seemed abrupt, the actual transition was more gradual as shown by the persistence of brackish sediments in the basal Hell Creek. Stanton concluded that the Fox Hills-Hell Creek contact was gradational and that any unconformities were local and of minor significance.

Leonard (1906) described the Upper Cretaceous section (Pierre through Lance (Hell Creek) at Iron Bluff, south of Glendive, Montana (site 2-4). Leonard collected fossil leaves from the upper Fox Hills strata that were misidentified as Tertiary by Knowlton of the U.S. Geological Survey. On the basis of this floral evidence, Leonard ascribed the Fox Hills strata to the Lance Formation and suggested that the apparent lack of the Fox Hills constituted a major unconformity. Calvert (1912) suggested that the strata directly above the Pierre, which were devoid of leaves, could represent the Fox Hills. Nonetheless, Calvert assigned 53 m of strata above the Pierre as the Colgate Member of the Lance Formation. The idea of the presence of a major unconformity was a facet of the "Cretaceous Boundary" problem.

Working at the extreme southern end of the anticline in South Dakota, Winchester et al. (1916, p. 18) noted that the white sand that they considered part of the upper Fox Hills had "been included in the Colgate sandstone member of the Lance Formation [by Calvert 1912], as mapped around the same anticline farther northwest".

Thom and Dobbin (1924) noted both the gradational contact between the Pierre and the "Lance" strata and the presence of Halymenities (= Ophiomorpha) major originally believed a seaweed but now known to represent the fossilized burrows of marine shrimp; Appendix B) in the "Lance" strata. As a result, Thom and Dobbin rejected the idea of a major unconformity and instead assigned 45 m of marine sediment above the Pierre, to the Fox Hills Formation. The term "Colgate" was restricted to the conspicuous white sand that comprised the upper 12 m of the Fox Hills section around the anticline.

Although never specifically stating it, Thom and Dobbin, in practice, placed the Pierre-Fox Hills contact where the shale of the Pierre changed upsection to silt and interbedded siltstone and claystone. The contact was not placed at the lowest sand as Stanton (1910) had done in the Missouri Valley. The upper contact was placed at the color difference between the white Colgate and the brown strata of the overlying Lance. This color difference formed a convenient basis to mark the marine to nonmarine transition.

The idea of a major unconformity between the Lance and Pierre or the Fox Hills and the Lance was rejected by Dobbin and Reeside

(1929) in a study of all Fox Hills exposures in the Missouri drainage.

Extending the contacts south from the Glendive area to western Bowman County, Hares (1928) and Dobbin and Reeside (1929) placed the Fox Hills-Lance contact at the top of the white Colgate sand, with color being the major criterion. Frye (1967) and Feldmann (1967), in accordance with the work of Laird and Mitchell (1942) in the Missouri Valley, placed the upper contact at the base of the first carbonaceous zone, thus objectively marking the change from marine to non-marine deposition. Subsequent workers have continued to employ this same criterion.

In Bowman County, all workers have followed the views of Stanton (1910) and have placed the Pierre-Fox Hills contact at the lowest occurrence of sand in the section (fig. 5). Hares (1928) was the first to report any observations concerning the Pierre-Fox Hills contact in the study area. He believed he observed the contact (contact of the Trail City and Timber Lake Members) at localities corresponding to sites 1, 2d, and 5a. He stated (p. 19):

The sandstone grades downward by alternation of beds of light sandstone and dark shale into the typical Pierre shale, so that it is almost impossible to be sure that the lower limit as determined is everywhere at the same horizon.

In practice, Hares drew the contact at the base of the lowest massive sand, thereby including any interbedded silt and clay in the Pierre. This was the case at the Little Beaver Creek exposures (site 1).

Feldmann (1967; 1972) placed the lower contact at the lowest

sand (site 2d; fig. 5) but noted a 3-m transition zone that he included in the top of the Pierre. Carlson (1979) identified a 2-m-thick transition zone at the same outcrop that he suggested be included in the base of the Fox Hills (fig. 5). However, he chose (p. 11, fig. 6) the contact at the same horizon as did Feldmann. In subsurface work to the east, Carlson (1979) included basal transitional strata in the Fox Hills (p. 12, pl. 2).

It has been the practice from the beginning at Glendive, and more recently at the remainder of Fox Hills exposures, to place the Pierre-Fox Hills contact at the change upsection from shale to silt, mixed silt-clay, or silt and clay interbeds. As of this writing, western Bowman County is the only area in the region where the contact is still placed at the base of the lowest sand. I have placed the Pierre-Fox Hills contact at the change from clay to silt thereby adding 10 m to the base of the formation for a total thickness of 37 m (fig. 3, 5).

Member terminologies.—The first complete member terminology emerged from the limited area of the Grand-Moreau divide in central Corson and Dewey Counties (historical type area), South Dakota, through the work of the South Dakota Geological Survey during the period 1945-1956 (fig. 4,6). In addition to defining the Trail City and Timber Lake Members, Morgan and Petsch (1945) suggested that the "banded beds" and the white sand unit which overlay them should be formalized as members. Consequently, through usage on state geologic quadrangle sheets, Curtiss (1952) formalized the white sand as the Colgate Member and Stevenson (1956) formalized the "banded beds" as the Bullhead Member. The Colgate, a member of the

Figure 6. Stratigraphic terminology presently applied to the Fox Hills Formation in the south half of the Williston Basin (modified from: Waage 1968, fig. 12; Bluemle et al. 1981). The terminology on the lefthand column was developed from Waage (1968) and reflects the stratigraphy on the southeast Basin rim (loc. 5-7) from (left to right) southwest to northeast; the column on the right is based on the earlier terminology and is still applied in outcrops all along the south rim and in subsurface work (Carlson 1979; 1982)

TYPE AREA TO MISSOURI VALLEY OF NORTH DAKOTA		MISSOURI VALLEY NORTH DAKOTA	STATEWIDE : NORTH AND SOUTH DAKOTA
WAAGE (1968)		KLETT AND ERICKSON (1976)	STATE GEOLOGICAL SURVEYS OF NORTH & SOUTH DAKOTA
		STATEWIDE IN NORTH DAKOTA	
SW	NE	CVANCARA (1976)	
IRON LIGHTNING MEMBER	COLGATE LITHOFACIES	LINTON ? MEMBER	COLGATE MEMBER
	BULLHEAD LITHOFACIES		BULLHEAD MEMBER
TRAIL CITY MEMBER	COLGATE LITHOFACIES		TIMBER LAKE MEMBER
	TIMBER LAKE MEMBER		
	IRISH CREEK LITHOFACIES		TRAIL CITY MEMBER
	LITTLE EAGLE LITHOFACIES	TRAIL CITY MEMBER	

Fox Hills since the work of Thom and Dobbin (1924) in the area south of Glendive on the Cedar Creek anticline, had recently been applied in the Missouri Valley of North Dakota by Laird and Mitchell (1942).

After expanding the type area to include Corson, Dewey and Ziebach Counties, Waage (1968) revised the initial "layer cake" system after a comprehensive study of the stratigraphy in this expanded region (fig. 3,6). Waage made use of the informal term "lithofacies" which he defined as follows:

... one or more bodies of sediment or sedimentary rock, distinguished from enclosing deposits by noteworthy lithologic, organic and/or structural characteristics ... and which were used to single out lithologic units essential for environmental reconstruction.

Waage delineated two lithofacies in the Trail City Member and both the Colgate and Bullhead Members were reduced to lithofacies and combined to form a new member, the Iron Lightning.

Erickson (1971; 1974) combined elements of Waage's terminology and the work of Fisher (1952) to produce a system that he applied in the Missouri Valley of North Dakota (fig. 6); Klett and Erickson (1976) added the Linton Member. Cvancara (1976) applied Klett and Erickson's system statewide in North Dakota but in actual practice its application has been confined to the Missouri Valley.

At present, the South and North Dakota Geological Surveys use the earlier terminology (Bluemle et al. 1981) although the South Dakota Survey is presently reevaluating this usage (Bretz 1983). Carlson (1982), affiliated with the North Dakota Geological Survey,

referred to the Colgate and Bullhead as members and included the Linton strata in the Colgate, thereby maintaining the earlier terminology.

Missouri Valley and type area.--In the Missouri Valley and type area the Fox Hills section consists of (figs. 3,6): (1) a northward-thinning wedge of silty to sandy clay (Trail City Member), that thins from 60 m in the southwest corner of the type area to 10 m or less in the Missouri Valley of North Dakota; (2) a north-northeastward-thickening wedge of sand (Timber Lake Member) that extends from the central portion of the type area and increases in thickness at the expense of the underlying strata to over 50 m in the Missouri Valley of North Dakota; (3) an upper unit (Iron Lightning Member), consisting of interbedded clay, sand and silt (Bullhead lithofacies) and a capping, stratigraphically variable, sand (Colgate lithofacies), that thins northward from 50 m in the southwestern corner of the type area to 30 m in the Missouri Valley of North Dakota. A sheet sand 2-5 m thick (Linton Member) caps the section in Emmons, eastern Sioux, and Corson Counties.

The lower Fox Hills (Trail City-Timber Lake) contains a rich fossil marine fauna, mainly ammonites and bivalves, which are found in calcareous concretions. In both areas, the upper Fox Hills (Iron Lightning Member) contains a restricted bivalve fauna. Waage (1968) and Speden (1970) dealt with the paleontology of the type area. In the Missouri Valley of North Dakota, Feldmann (1967; 1972) described bivalves and Erickson (1971) reported on gastropods.

The Trail City Member was originally defined by Morgan and Petsch (1945) in the vicinity of Trail City in Dewey County as the basal member of the Fox Hills in the type area. The unit, consisting of sandy shale containing three to five, locally continuous zones of fossiliferous concretions (Little Eagle lithofacies), was previously considered part of the upper Pierre (Stanton 1910). Fisher (1952) introduced the member to the Missouri Valley of North Dakota, but Feldmann (1967; 1972), following Waage (1961), considered the member too thin to recognize in North Dakota, and included the strata in the overlying Timber Lake. In the type area, Waage (1968) divided the member into two lithofacies: the Irish Creek in the southwest and the Little Eagle in the northeast and east. The Irish Creek lithofacies consists of an upper half, laterally equivalent to the Timber Lake Member, which is composed of massive clay, silt and very fine sand and a lower half, equivalent to the Little Eagle lithofacies, that consists of massive light gray clay, silt and very fine sand, interbedded clay and silt, and contains three to five locally continuous zones of fossiliferous concretions.

In the type area, the lower contact of the member is chosen at the obvious increase of silt in going upsection (Waage 1961). In the southwest, the upper contact is drawn where the mixed Irish Creek strata meet the interbedded Bullhead lithology; in the northeast the contact occurs where the mixed fine sediment of the Little Eagle meets the basal glauconitic sand of the Timber Lake Member.

In Emmons County, Erickson (1971) designated 6 m of sand, siltstone, and bentonitic clay as the Trail City. The

section was incomplete. The member contained no concretions, and the upper contact was placed at the basal sand of the Timber Lake.

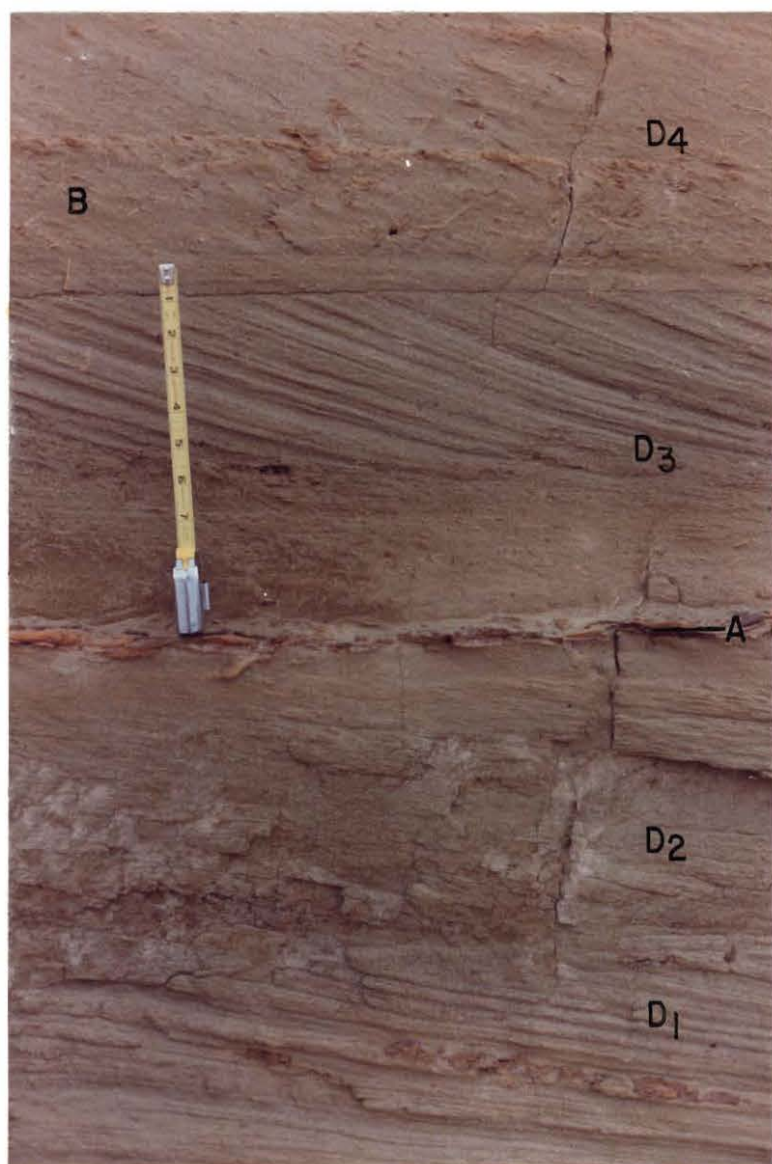
The Timber Lake was originally defined by Morgan and Petsch (1945) as 28 m of sand overlying the Trail City Member in the vicinity of Timber Lake in Dewey County. Fisher (1952) introduced the member in Sioux County. In the type area, Waage (1961) noted that the member was absent from the southwest and that it increased in thickness to the north and northeast at the expense of both the Bullhead and Trail City. The concretion zones of the Trail City are continuous into the Timber Lake.

In the type area, the Timber Lake consists of poor to well sorted, fine to medium sand that weathers to a yellow or orange brown; randomly scattered fossiliferous concretions are especially common near the base. The upper half of the member, the Tancredia-Ophiomorpha biofacies, is characterized by abundant ferruginous ledges of mudstone or sandstone, trough and tabular cross-stratification, and abundant ferruginous Ophiomorpha burrows (fig. 7,8). The base of the member is often characterized by a thinly interbedded or mixed sand to clay transition zone. The contact with the underlying Trail City occurs at a major, often glauconitic, sand. The upper contact is drawn at the lowest appearance of interbedded sand and clay (Bullhead lithofacies).

In the type area, Waage (1961) demonstrated, as had Laird and Mitchell (1942) in Morton County, North Dakota, that the Bullhead and Colgate were lateral facies of one another. Waage (1968)

Figure 7. The Timber Lake Member in the Missouri Valley of North Dakota (site 7-2, loc. 7 on fig. 1, 3). Layers of trough cross-bedding are evident with the major event boundaries marked by ferruginous, irregular boxworks of O. nodosa form B. These strata are similar to those at the type locality of the member in South Dakota and have been interpreted as barrier bar deposits (Waage 1968; Feldmann 1967, 1972; Erickson 1971). O. nodosa occurs in the normal-bedded sub-facies of the hummocky-bedded facies (Timber Lake Member) in the study area. Pick is approximately 1 m.

Figure 8. Sedimentary structures in the Timber Lake Member in the Missouri Valley of North Dakota (site 7-2, loc. 7 on fig. 1, 3). Trough cross-bed sets occur at (D₁₋₄); rip-up clasts occur in the foresets in (D₁). The wavy layer at (A) marks a sequence top (event boundary); the zones above (A) and at (B) contain the interevent bioturbation of O. nodosa form C. The tape is 25 cm.



referred to the Bullhead and Colgate as lithofacies and combined them to form the Iron Lightning Member, a usage that is not universally accepted.

Searight (1934) initially dubbed the Bullhead strata the "banded beds" since they were composed of light sand and dark shale. Stevenson (1956) formally named the member after the town of Bullhead in central Corson County, South Dakota.

The Bullhead is composed of 3-30 cm thick interbeds of fine to medium, white to gray sand and silt, and brown to gray clay (fig. 9). The bedding is often contorted and biogenic remains are sparse, consisting mainly of fecal pellets and plant fragments that are concentrated along bedding planes.

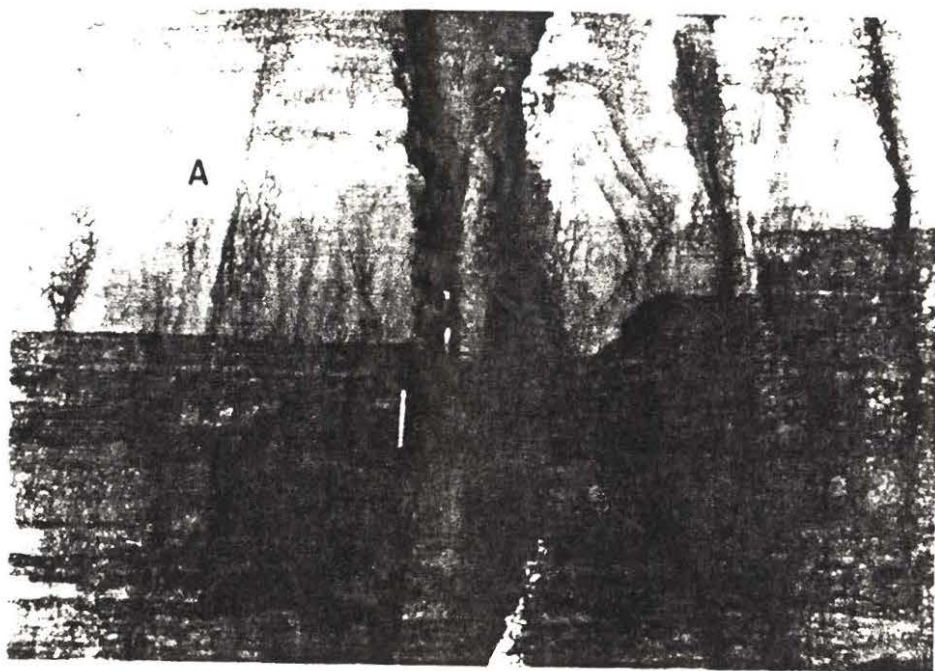
The Bullhead is overlain by the Colgate, the Linton Member or the Hell Creek formation.

The Colgate was defined at the north end of the Cedar Creek anticline and was the first member defined for the Fox Hills (Thom and Dobbin 1924); it was introduced to the Missouri Valley of North Dakota by Laird and Mitchell (1942) and to the type area by Curtiss (1952).

In the type area the Colgate is composed of light-gray weathering, very fine to medium, lithic sand. Tabular and trough cross-bedding are common, with the lower bounding surfaces accentuated by clay or carbonaceous layers often bright orange from iron oxides. Plant debris is common along with 0.3-4 m in diameter, ovoid concretions that often form ledges.

Figure 9. The Bullhead lithofacies of the Iron Lightning Member, at the type locality of the Iron Lightning Member south of Iron Lightning, South Dakota (site 5-1; loc. 5 on fig. 1, 3). Sands, interbedded with wavy or lenticular bedding are cut out by the major sand lentil at (A); the complete lentil is 0.8 by 10 m, and has a planar erosional contact with the underlying wavy bedded "pavement". Wavy layers occur in the upper third of the sand lentil. Deformation structures, water escape structures, and oyster accumulations (not visible in the figure) all occur laterally in the sand lentil. The Bullhead lithofacies has been interpreted as a delta topset or foreset deposit (Waage 1968; p. 156) or as a lagoon deposit (Feldmann 1967; 1972). The ruler is 15 cm.

Figure 10. The contact of the Fox Hills Formation (Colgate lithofacies of the Iron Lightning Member) and the overlying Hell Creek Formation (Crowghost Member) at the Crowghost Cemetery, Sioux County, North Dakota (site 7-1; loc. 7 on fig. 1, 3). The contact (A) occurs between the carbonaceous sand of the Crowghost, containing tree stumps in growth position, and the underlying gray, fine to medium sand of the Colgate characterized by trough cross-bedding. Ophiomorpha occurs ~~both in the Colgate and in the Brelen member~~ of the Hell Creek indicating that brackish environments persist to a horizon 10-18 m above the Fox Hills-Hell Creek contact. The thickness of the Colgate, from the base of the cliff to the level of the contact, is 12 m.



In the Missouri Valley of North Dakota, the Colgate is well exposed only at Crowghost Cemetery on the Cannonball River in north-central Sioux County (fig. 10). There, the unit is 12 m thick and composed of fine to medium, light olive gray sand that contains ferruginous and carbonaceous drape structures, and near the base the ichnofossil Ophiomorpha. Trough cross bedding is the dominant sedimentary structure. The unit is conformably overlain by the Hell Creek; the basal contact with the Bullhead is unconformable.

Referred to by Fisher (1952) as the "datum sand" and later by Erickson (1971) as the Unnamed Member, the Linton Member was named and defined by Klett and Erickson (1976), who considered it equivalent to Bed Q. Waage (1968) and Carlson (1982) included this unit in the Colgate. According to Klett and Erickson the member averages 2 m thick and caps the Fox Hills section in Emmons, eastern Corson, and Sioux Counties.

The Linton Member is composed of light olive-gray to gray-brown, fine grained moderately to poorly sorted, indurated siliceous sandstone. The unit is generally massive but contains some horizontal and trough cross-stratification. Roots, wood fragments, Equisetum, and Ophiomorpha borneensis (?) occur in the member.

The Linton Member is the butte-capping, sheet sandstone that lies above the Bullhead (and perhaps the Colgate lithofacies) and below the lignitic horizon marking the base of the Hell Creek.

Cedar Creek anticline.--In the Glendive area, the Fox Hills section consists of 30 m of interbedded silt and claystones, (Timber Lake Member) overlain by 12-24 m of very fine to medium sand

(Colgate Member) (Butler 1980; fig. 3). The Colgate strata ^{are} ~~were~~ arranged in multi-story, multilateral, 6-m thick upward fining sequences (from the base): lag to tabular-bedded (2 m); wedge-bedded (2 m); and ripple, lignite, and shale (2 m) (fig. 3, 11, 12).

On the south end of the anticline, the Fox Hills section has been traditionally defined as a coarsening-upward sequence consisting of 27 m of very fine to medium sand, and has been divided into the Timber Lake Member, the basal 14 m, and the overlying Colgate Member (fig. 3, 5). The Trail City has been tentatively applied in the study area (fig. 5); the Bullhead strata are not present west of Bowman, North Dakota (Carlson 1979; fig. 3).

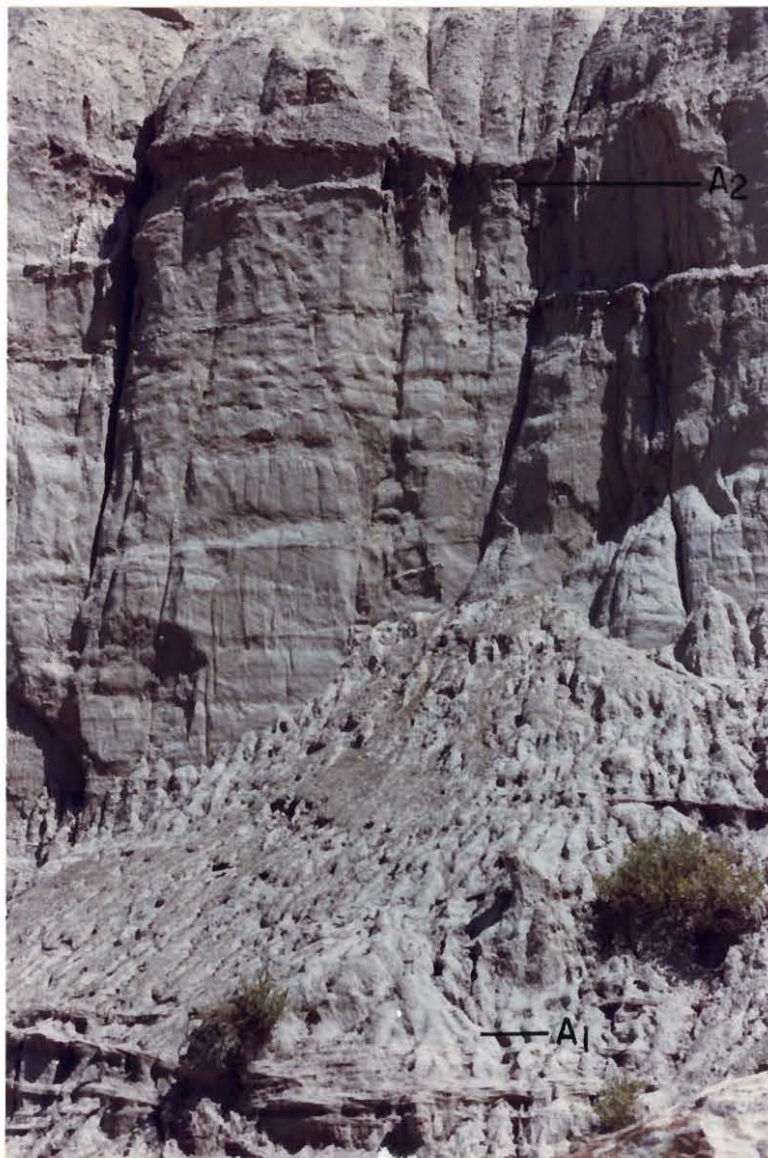
Feldmann (1967; 1972), following Waage, did not recognize the Trail City in North Dakota. However, he did note a 3-m transition zone at the base of the Timber Lake at site 2d (fig. 5).

In the subsurface, Carlson (1979) noted a substantial zone of transition between the Pierre and Timber Lake that was recognized from spontaneous potential and resistivity logs. This zone was assigned as the Trail City Member. Carlson suggested that the basal 2 m of the Timber Lake was equivalent to this subsurface zone at site 2d (fig. 5).

At site 2d, Feldmann (1967, 1972) assigned 14 m of fine grained buff to yellow, fine to medium sand to the Timber Lake Member. The lower half of the member contained chocolate-brown shale interbeds and the upper half contained cross-bedding and discontinuous, ferruginous sandstone ledges (fig. 5). Carlson (1979) agreed with this assignment.

Figure 11. The Colgate Member of the Fox Hills Formation (site 2-3, loc. 2 on fig. 1, 3) at Glendive, Montana, two kilometers east of its type locality. Carbonaceous foreset toes and claystone pebble and cobble lags occur at (A_1); trough cross-bedding is visible (B). The 6 m of strata between (A_1) and (A_2) are interpreted as a channel sequence (Butler 1980; Wilde 1983).

Figure 12. Sedimentary structures in the Colgate Member (site 2-5, loc. 2 on fig. 1, 3) near Glendive, Montana, two kilometers south of the type locality. Claystone pebble and cobble lags (A) occur at the base of trough cross-beds. These strata form the basal part of a channel sequence (Butler 1980; Wilde 1983). The pick is approximately 1 m.



Thom and Dobbin (1924) defined the Colgate as a member of the Fox Hills in the area between Iron Bluff and Glendive (type locality). The Colgate was restricted to the 12-m thick "conspicuous white, upper sandstone of the Fox Hills" that contained both Halymenites (=Ophiomorpha) major and leaf imprints in exposures around the anticline. They believed that the unit marked the highest occurrence of marine strata in the Cretaceous.

Using the "white" color as a convenient criterion, Hares (1928) introduced the Colgate to the study area (sites 1a, 1b, 2d and 5a; fig. 2, 5), noting that both the Colgate and the unnamed strata below contained Halymenites (=Ophiomorpha) major. Dobbin and Reeside (1929) mislabeled the entire Fox Hills section (site 1b) as Colgate.

Feldmann (1967; 1972) described the Colgate as 12 m of "dirty, white sandstone" containing lignitic shale partings and exhibiting fluted weathering. The weathering pattern and lignitic partings were considered diagnostic. Carlson (1979) concurred with this description.

In this study, contrary to previous usage, the Fox Hills Formation is treated as a 37-m-thick unit that consists of two parts (fig. 3, 5): a basal, 10-m-thick, silt and clay unit (Trail City Member), here considered as part of the Fox Hills for the first time, and an overlying 27-m-thick unit (Timber Lake and Colgate Members), composed of very fine to medium sand, that comprises the formation as it had previously been defined.

Methods

Field methods

Field work, in the form of reconnaissance and outcrop description, was pursued at Fox Hills outcrops all along the south rim of the Williston Basin. The outcrop areas outside of the study area that I studied (fig. 1, 3)—Fort Peck (site 1), Glendive (sites 2-1 through 8), Hammond, and Forsythe in eastern Montana; Meade County (sites 4-1 through 3) and the type area (sites 5, 6) in South Dakota; and the Missouri Valley of North Dakota (sites 7-1 and 7-2)—are listed and described in Appendix A, part 1. Measured sections of the Fox Hills Formation in the study area (sites 3-1 through 7; fig. 2) are characterized in Appendix A, part 2, on 23 columns with accompanying descriptions.

Topographic maps are available for the entire study area (Appendix A, part 2). The location of outcrops and the delineation of stratigraphic units was assisted by aerial photographs. Only early maps (Hares 1928, pl. 14; Erdmann and Larsen 1934) provided detailed coverage of the geology of the study area. In Montana, the reconnaissance of the Hammond area was assisted by a recent geologic map (Bergantino 1980); the early map by Dobbin and Larsen (1934) provided detailed coverage of the Glendive area.

Outcrop characterization.—At the outcrop, the Fox Hills section was divided into informal units based on sedimentary structures. The descriptions of these units included information on lithology, color, texture, and sedimentary structures (type,

dimension, and direction). Selected outcrops and outcrop features were photographed. Ichnofossils and body fossils were collected, identified, and their relative abundance noted; bioturbation zones were measured, and their constituents and distribution noted.

Sections were measured with a hand level, and a 12- or 100-foot tape; all figures were converted to metric. Color was determined with a rock-color chart (Goddard et al. 1963). Grain size was estimated by feel, hand lens observation, and by the use of a sand gauge. Directional measurements (strike, dip, azimuth) were obtained with a Brunton Compass.

Lithologic sampling.--Lithologic samples were gathered to determine the degree of horizontal and vertical textural variability as well as the mineralogy of the nonindurated sands of the upper 27 m of the formation. Samples were collected at horizons (typically 1 to 3 m apart) determined by a random number table; three samples were taken along each horizon at 1-to 3-m intervals. A total of 99 samples were collected from three outcrop sites (1b, 4, and 7); sampling horizons are shown on the columns in Appendix A, part 2.

Originally, since the aim of the sampling was general characterization, the Fox Hills sands were considered as a single population. However, it became apparent, through the evaluation of sedimentary structures (notably hummocky bedding) that the bulk of the sands occurred in a series of stacked, graded beds; each bed contained a sequence of three or four sedimentation units as defined by Otto (1938). Random sampling of the outcrop could have resulted in the gathering of the sand samples representing disparate energy

conditions (grains from ripples and hummocky stratification for example) from a single graded bed. In view of this, samples were collected from similar bedforms at each horizon.

Laboratory Methods

The laboratory work consisted of textural and mineralogic analysis. Samples of indurated sand and shale were examined with a binocular microscope. Minute features, such as lamination, variation in mineral distribution, and the abundance of matrix were noted in order to enhance the determination of environments of deposition.

Textural analysis.--Although 99 lithologic samples were collected only 74, typically muddy sands, were analyzed for texture by the sieve and hydrometer techniques; the methods of Carver (1971) and Folk (1975) were used in the analyses. Samples containing a large amount of carbonaceous material or those that were bioturbated were discarded.

The samples were disaggregated manually and split to 50 to 60 g lots. They were then soaked in 10% Calgon solution to disassociate clays; wet sieving followed, which divided the silt-clay fraction from the sand fraction. The sand fraction, after drying, was sieved at 1/4 phi intervals on the Ro-tap. The silt-clay fraction from wet sieving was combined with the pan fraction from dry sieving for the hydrometer analysis; readings were taken for the 5-phi fraction (coarse silt) and at the silt-clay boundary.

The size fractions were converted to percentiles and plotted on histograms. Subsequently, the percentiles were plotted on triangular sand-silt-clay diagrams. The sand fraction percentages were plotted on probability ordinate paper and graphic standard deviation and

graphic skewness were then calculated (Folk 1975, p. 46-7).

Textural data are provided in Appendix C.

Mineral analysis.--The recombined sand fraction from 15 samples was saved for mineralogical analysis. The samples were split to 3 g and a portion of each split was attached to a glass slide with double-sided tape to form a grain mount. Mineral types were characterized and identified by microprobe. Two hundred points were counted for each slide. The point counts were converted to percentiles, combined into the proper mineral clans (i.e., feldspars, quartz, and rock fragments), and plotted on a trilinear diagram to derive a mineralogical name for the sediment (Folk 1975, p. 129).

PALEONTOLOGY

Stanton (1910) reported Leda (Yoldia) evansi, Tellina scitula, Entalis (?) paupercula, and Halymenites (=Ophiomorpha) major from the Fox Hills Formation along Little Beaver Creek south of Marmarth. Only the ichnofossil Ophiomorpha has been noted by subsequent workers.

With the exception of leaf remains, no body fossils were observed in the Fox Hills section during the course of this study. The majority of remains in the study area consist of abundant examples of a limited suite of ichnofossils of which species of Ophiomorpha are the most plentiful and widespread. The trace fossil suite contains (fig. 13, 14): dwelling traces, including a single example of Thalassinoides (?) and numerous examples of two species of Ophiomorpha, O. nodosa and O. borneensis; the grazing trace Cosmorhaphis; and unidentified feeding structures. Leaves, notably Dryophyllum (?), horsetail stems (Equisetum), and root molds occur at the top of the formation (fig. 13, 14). The Systematic Paleontology is contained in Appendix B.

Figure 13. Summary of the fossils observed or collected in the study area. The species of Ophiomorpha are the most abundant and widespread forms. Figure 14 shows the distribution of the fossils; Appendix B contains the Systematic Paleontology.

	Taxon	Interpretation (Ethology)
Flora	<u>Dryophyllum</u> (?)	leaves
	<u>Equisetum</u> (?)	horsetail stems
	root molds	plant roots
Ichnofossils	<u>Ophiomorpha borneensis</u>	
	<u>Ophiomorpha nodosa</u>	
	forms A, B, and C	dwelling burrows (domichnia)
	<u>Thalassinoides</u> (?)	
	Unidentified burrows	feeding burrows (fodinichnia)
	<u>Cosmorhaphe</u>	grazing trails (pascichnia)

SEDIMENTOLOGY

The Fox Hills Formation contains three facies based on sedimentary structures (from the base; fig. 14)--massive-hummocky, hummocky bedded, and cross-bedded--that are further characterized by grain size, sorting, and paleontology. These sedimentary structure facies form the basis for the definition of members and the interpretation of depositional environments. The formation is also divided into upper and lower portions--the lower characterized by hummocky bedding and the upper containing cross-bedding.

Inorganic Sedimentary Structures

Inorganic primary sedimentary structures--surface markings, penecontemporaneous deformation structures, bedforms, and bedding--are those formed at the time of deposition or shortly afterward and before consolidation of the sediments (Pettijohn and Potter 1964). In the Fox Hills Formation of the study area, three sedimentary structures--wavy bedding, hummocky bedding, and cross-bedding--are abundant (fig. 14). Hummocky bedding, the major bedding type in the formation, is confined to the lower Fox Hills.

Wavy bedding

Wavy bedding is a composite, heterolithic bedset characterized by (fig. 15, 16; Reineck and Singh 1975, pp. 98-99, 103):

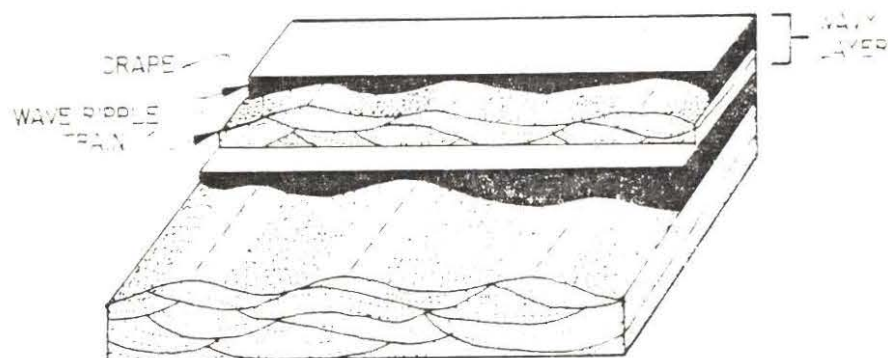
- (1) alternating, mud drape and sand ripple layers that are horizontally continuous and vertically isolated;
- (2) mud drapes that

Figure 14. The characteristics of the sedimentary structure facies in the Fox Hills Formation in the study area. The facies are defined on the basis of sedimentary structures, but are further characterized by sediment textures and biota. The lower Fox Hills is dominated by hummocky bedding; the upper Fox Hills by cross-bedding. The upper Fox Hills is separated from the adjacent strata by unconformities. The sedimentary structure facies form the basis for the formal stratigraphic units and the interpretation of environments. Unconformities are denoted by "U"; conformities by "C".

SEDIMENT		SEDIMENTARY STRUCTURES		BIOTA		SEDIMENTARY STRUCTURE FACIES				
Sublithic to Subarkosic Muddy Sand	70 - 85 percent sand ; v.fine - medium ; moderate to poorly sorted ; relatively high lateral variation in texture	HUMMOCKY - BEDDING WAVE RIPPLES (WAVY LAYERS) CROSS - BEDDING	HUMMOCKY - BEDDING WAVE RIPPLES (WAVY LAYERS) CROSS - BEDDING	DRYOPHYLLUM, EQUISETUM ROOT MOLDS		(BARREN)	CROSS - BEDDED FACIES	U	37m	
	RARE AND ISOLATED									
	70-90 percent sand ; v.fine - fine ; moderate sorting			O. BORNEENSIS	OCCUR IN THE UPPER PORTIONS OF HUMMOCKY BEDS	ZONED BIOTURBATION	HUMMOCKY-BEDDED FACIES	AMALGAMATED SUBFACIES	U	29m
	50-70 percent sand ; very fine sand ; moderate sorting								O. NODOSA FORMS A, B, C	C
< 20 percent sand ; sandy mud	COSMORHAPHE	MASSIVE - HUMMOCKY FACIES	C							
silt and clay			MASSIVE, MOTTLED OR FINELY INTERBEDDED, GRADATIONAL BEDDING PLANES.				MIXING INDICATES BIOGENIC ACTIVITIES BUT NO TRACES RECOGNIZABLE			
										UPPER FOX HILLS FM.
										LOWER FOX HILLS FM.

Figure 15. Wavy bedding. Wavy bedding consists of two or more wavy layers each composed of a ripple (here wave ripples) overlain by a drape. Wavy bedding occurs as W zones atop hummocky beds (fig. 20) and is associated with cross-bedding in the upper Fox Hills. Wavy bedding is a low energy bedform — the drapes indicate slack-water following ripple formation — resulting from a single episode of deposition (Hawley 1981; p. 150).

Figure 16. Wavy bedding in the lower Fox Hills (hummocky-bedded facies). Four well developed wavy layers are apparent in this W zone. Pencil is 11 cm.



almost completely fill ripple troughs and make a thin cover over the ripple crest, thereby forming a nearly horizontal upper surface; and (3) the presence of many alternating sand ripple and drape couplets. A single ripple-drape couplet constitutes a "wavy layer" (Reineck and Singh 1975, p. 100). Lenticular bedding resembles wavy bedding except that the sand ripple layers are discontinuous (Reineck and Singh 1975, p. 100-1).

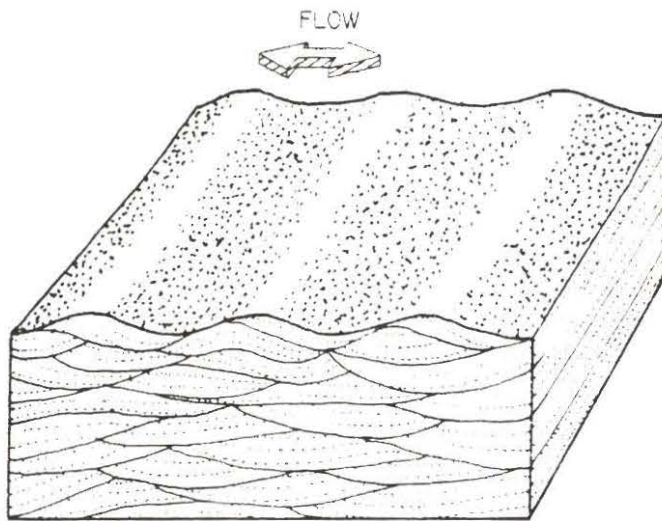
Wavy bedding is a major component of the lenticular subfacies, forms W zones at the top of hummocky beds (see hummocky bedded facies) in the normal-bedded and amalgamated subfacies, and occurs in the cross-bedded facies (fig. 14).

Drapes.--The term "drape" refers to a clay or mud layer, typically exhibiting normal grading, that "mantles" or "drapes" the relief of a deposurface. Occurring as an integral component of wavy layers or bedding in the study area, the layers are 1-2 cm thick, have a sharp lower contact with the underlying ripple surface, and an upper contact that is planar and erosional (fig. 15, 16).

Wave ripples.--Wave ripples are characterized by the following (fig. 17; Boersma 1970 in Reineck and Singh 1975, pp. 24-28, 89; Harms et al. 1975, p. 58): (1) catenary to arcuate lower bounding surfaces; (2) tangential low angle foreset laminae arranged in "bundles", a result of the preservation of foreset laminae; (3) foreset laminae that are often wavy, having offshoots that originate at one peak and continue over the next peak; (4) synchronous sets that contain laminae arranged in opposing directions (form discordant) or erosive forms; and (5) near symmetrical surface morphology.

Figure 17. Wave ripples (modified from Harms et al. 1975, fig. 3-7). Wave ripples occur alone in the X zones and in wavy bedding in the W zones of hummocky bedding (fig. 20) or in wavy bedding in the upper Fox Hills. Wave ripples are a low energy bedform produced by oscillating wave motion in the absence of currents (Harms et al., 1975; p. 150).

Figure 18. Wave ripples in hummocky bedding. The horizontal laminae of the F zone occur at A overlain by wave ripples at B. The ripple layer and overlying drape constitute a wavy layer. Pencil is 9 cm.



In the Fox Hills Formation, wave ripples are associated with drapes in wavy bedding and form the X zone of hummocky beds (fig. 18). Wave ripples do not occur in the strata below the hummocky-bedded facies (fig. 14).

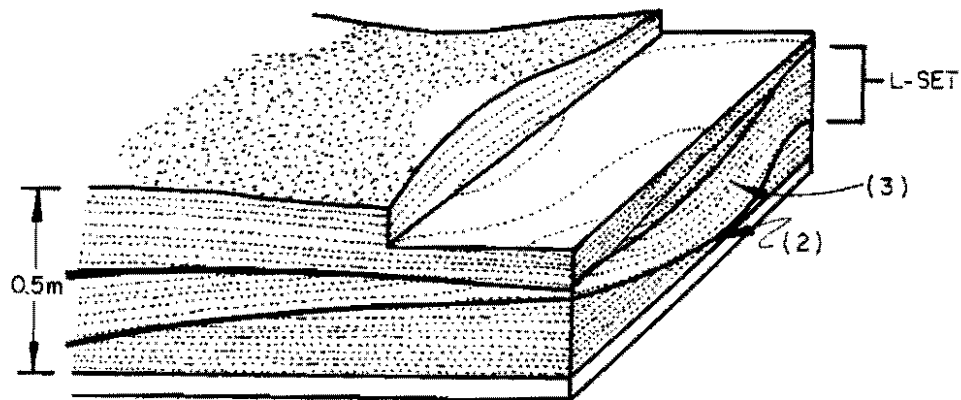
Hummocky stratification

Hummocky stratification has been previously referred to as "truncated wave ripple lamination" by Campbell (1966) and "truncated megaripples" or "ripple and trough laminations" by Howard (1972). The bedform was defined and referred to as "hummocky" by Harms et al. (1975) from examples in the Cretaceous Gallup Sandstone. The bedform occurs as laminae-sets (L-sets) in silt to medium sand and is characterized by the following (fig. 19; Harms et al. 1975, p. 87-89; Dott and Bourgeois 1982, pp. 664-665): (1) erosional lower bounding surfaces that commonly slope at angles of less than 10 degrees, though dips may be as high as 15 degrees; (2) laminae that are nearly parallel to the lower bounding surface, never intersecting it; (3) laminae that exhibit systematic lateral thickening in a set, so that their traces on a vertical surface are fan-like with a regularly decreasing dip; (4) variable dip directions for set bounding surfaces and the overlying laminae so that no preferred direction is evident; and (5) laminae that may continue from swale to swale, mantling a series of hummocks and swales.

The basic bedform of hummocky stratification is the laminae-set (L-set; fig. 19). Since the laminae in each L-set dip at low angles and exhibit synforms and antiforms about elliptical swales and hummocks and never truncate on a lower bounding surface, hummocky

Figure 19. Hummocky stratification (modified from Harms et al., 1975, fig. 5-5). The basic bedforms of hummocky stratification is the L-set (Dott and Bourgeois 1982). The L-set contains third order surfaces (lamina to lamina contacts) and is bounded by second order surfaces. L-sets comprise the H zone of hummocky bedding (fig. 20). Hummocky stratification is deposited under the combined influence of suspension fallout and oscillatory motion (p. 151).

Figure 20. Hummocky bed (modified from Dott and Bourgeois 1982, fig. 3). Hummocky beds can be bounded by first or second order surfaces. Hummocky bedding is deposited from suspension fallout in the presence of oscillatory motion in the wake of a high energy event (p. 151).



- (2) SECOND ORDER SURFACE - L-SET to L-SET CONTACT
 (3) THIRD ORDER SURFACE - LAMINA to LAMINA CONTACT

		ZONE DESIGNATION	
		UNBURROWED	BURROWED
HUMMOCKY BED	(1)	W	Wb
	(1) or (2)	X	Xb
		F	Fb
	(3)	H	Hb
	(2)		
	(1)		
<p>(1) FIRST ORDER SURFACE - BED to BED CONTACT (2) SECOND ORDER SURFACE - BEDFORM to BEDFORM CONTACT (3) THIRD ORDER SURFACE - LAMINA to LAMINA CONTACT</p>			

stratification is considered a type of horizontal lamination instead of cross-stratification (Hamblin 1979; Bourgeois 1980). Large-scale and small-scale forms occur. Laminae-sets occur grouped in tabular layers (hummocky zones = H zones); each L-set is bounded by erosional contacts (fig. 19).

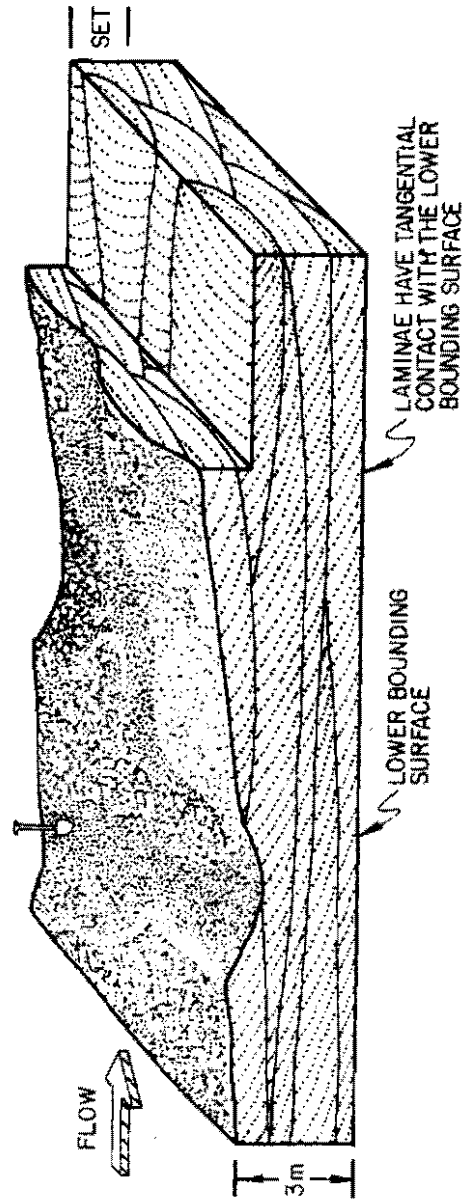
Hummocky bedding.—Zones of hummocky L-sets are associated with other bedforms in a relatively consistent, heterolithic, composite bed sequence termed "hummocky bedding" (Dott and Bourgeois 1982). An idealized hummocky bedding sequence--in the vein of the Bouma sequence--has been synthesized from examples in the rock record (fig. 20; Dott and Bourgeois 1982, fig. 3, pp. 666-669). Stacked, tabular hummocky beds comprise the strata of the hummocky bedded facies and occur throughout the lower Fox Hills.

Hummocky beds are bounded at the base by sharp erosional planar contacts marking the bases of hummocky zones (H zones). These zones are overlain by flat laminae (F zone) over which lies a zone of ripples (X zone). In the study area, the sandy HFX sequence is overlain by wavy layers, here termed W zones; hummocky beds are normally overlain by mudstone (M zone). The F and X zones are continuous extensions of the H zone; no contact separates these layers. W zones may be continuous with the underlying bed or be separated from it by a scour surface.

Cross-bedding

Two types of cross-bedding--trough and epsilon--occur in the upper Fox Hills of the study area (fig. 14).

Figure 21. Trough cross-bedding (modified from Harms et al, 1975), fig. 3-1). In contrast to hummocky stratification, the foreset laminae in trough bedding truncate upon the lower bounding surface, but in transverse view the two bedforms may appear to be similar. Trough cross-bedding is an upper flow regime unidirectional bedform resulting from scour filling or dune migration (p. 153).



Trough cross-bedding.--Trough cross-bedding is characterized in the following way (fig. 21; Harms et al. 1975): (1) laminae fill elliptical troughs; (2) in a longitudinal section, the laminae are parallel and dip in a single direction within each set, but in transverse section the laminae occur as parallel-symmetrical or non-symmetrical, concave-up arcs; (3) the bounding surfaces between sets are erosional and may be planar, angular or scoop shaped; (4) the laminae may be angular, tangential or concave-up in their contact with the lower bounding surface, becoming more tangential in finer grain sizes; and (5) the laminae dip in their steepest portion at 25-30 degrees. In the study area the bedform occurs grouped as cosets or as isolated scoop-shaped sets in horizontal lamination.

Epsilon cross-bedding.--Epsilon cross-bedding (Allen 1963, p. 102-103, fig. 3D) is characterized as follows: (1) the units are large scale and solitary; (2) each unit is typically underlain by a planar erosional surface; (3) the foreset laminae are lithologically heterogenous, consisting of couplets of coarse overlain by fine grained sediment; and (4) in vertical section parallel to the maximum dip direction, the foresets are straight to convex-up.




Sand Petrology

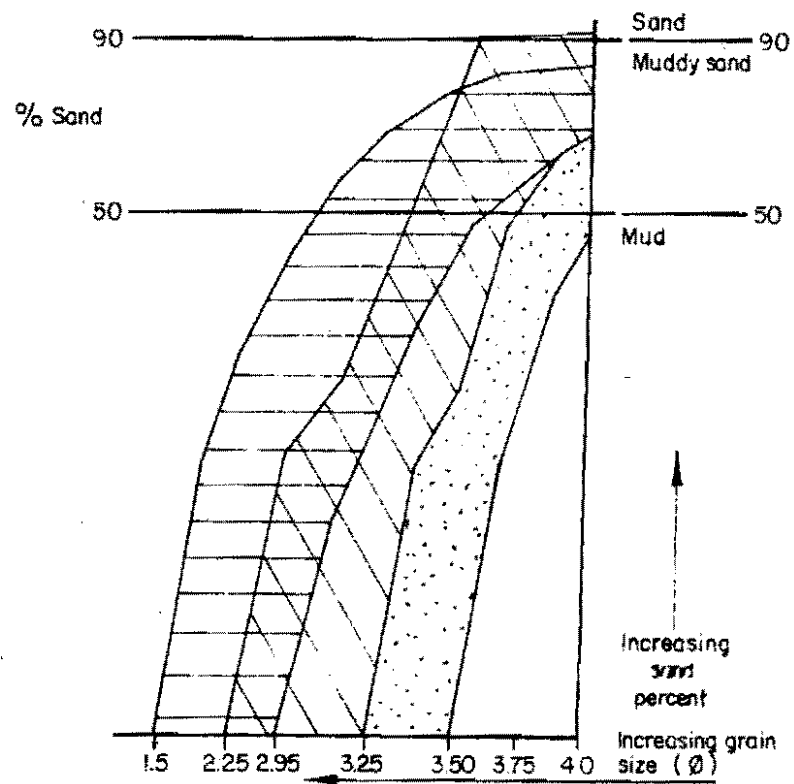
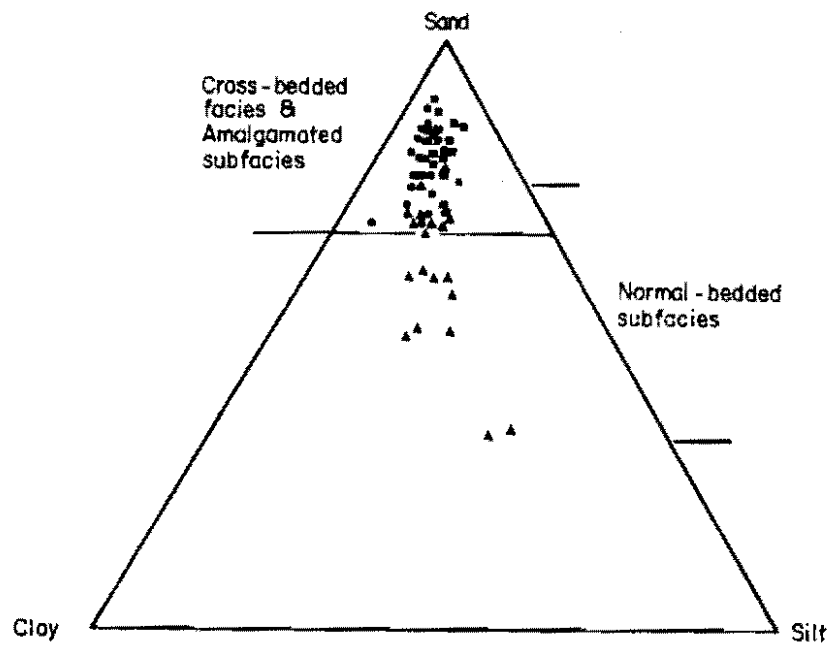
This section provides a general characterization of the petrology of the unconsolidated sand strata (hummocky bedded and cross bedded facies) that comprise the upper 27 m of the Fox Hills in the study area. The sediment is mainly muddy, sublithic or subarkosic, very fine to medium sand; very fine sandy mud occurs at the base of

Figure 22. Grain size distribution in the sand portion (hummocky-bedded and cross-bedded facies) of the Fox Hills Formation in the study area. Clay and silt occur in near equal amounts; the percentage of sand increases upsection through the hummocky-bedded facies.

LEGEND		
Cross bedded facies		●
Hummocky-bedded facies	amalgamated subfacies	■
	normal-bedded subfacies	▲

Figure 23. The sand grain-size populations of the sedimentary structure facies. The curve envelopes are plotted on probability ordinate paper. Grain size increased steadily in the hummocky-bedded facies; the plot of the cross-bedded facies envelope overlaps the field of the amalgamated subfacies.

LEGEND		
Cross-bedded facies		
Hummocky-bedded facies	amalgamated subfacies	
	normal-bedded subfacies	



the sand section.

Texture

The data for the following generalizations are contained in Appendix B. For sediments at the base of the section, the sorting values and the percentage of the silt-clay fraction may seem at odds, but these sediments are composed of very fine sand and coarse silt that is moderately sorted.

In the muddy sand strata of the formation (fig. 22, 23):

(1) the percent of matrix decreases upsection through the hummocky facies from 50 to 10-20 percent whereas the cross-bedded facies contains 15-30 percent matrix; (2) moderate sorting characterizes the sediments of hummocky facies whereas the cross-bedded facies contains moderately to poorly sorted sediment; (3) the median grain size increases upsection from 4.0 ϕ (base of the hummocky facies) to 2.80 ϕ (top of the hummocky bedded facies) to 2.30 ϕ (cross bedded facies); (4) lateral variability in texture is low in the hummocky bedded facies but relatively high in the cross bedded facies; and (5) the sediments are strongly positively skewed throughout the section.

Mineral composition

The mineral composition of the sand fraction of the muddy sand section is typically 70 to 85 percent quartz, and 10 to 20 percent each of feldspar and chert. Muscovite, biotite, and hornblende are common accessory minerals. Since neither chert nor feldspar is clearly dominant, both subarkosic and sublithic sand occur.

Quartz occurs in two forms: as clear, glassy, equant to irregular, subrounded to angular grains, and as similar grains with black inclusions. The first type is the most abundant, comprising 60-80 percent of the sand fraction.

Feldspar, orthoclase and sodic plagioclase, and chert are the next most abundant grain types. Feldspar grains are: white, pink, or tan; exhibit silky luster on fresh surfaces; are equant to irregular; angular to subrounded; and are typically badly weathered. Chert is characteristically white to tan, "milky" grains that are angular to subrounded.

Biotite and muscovite sediment occur as oversize "books" comprising the coarsest fraction of the sediment, with rounded edges. Biotite may be badly weathered. Hornblende occurs as black rods, angular and typically weathered.

Microprobe analysis shows that feldspars are typically badly weathered with many largely decomposed to illite, a common weathering product in arid climates. The white to tan weathering product is present in sediments throughout the section but is readily visible in the sediments of the cross-bedded facies, probably a result of the larger grain size.

Inorganic Sedimentary Structure Facies

Three major facies can be delineated on the basis of their primary inorganic sedimentary structures (fig. 14). From the base of the formation, the facies are as follows: massive-hummocky, hummocky-bedded, and cross-bedded. The hummocky-bedded facies contains three

subfacies (from the base): lenticular, normal-bedded, and amalgamated. Wavy bedding is a minor, but important, component of the hummocky-bedded and cross-bedded facies.

Massive-hummocky facies

The massive-hummocky facies is characterized by two components (fig. 24): tabular, sandy-silt hummocky layers, and mixed silt-clay in massive units. The facies averages 10 m thick; the full section is exposed only at the Little Beaver Creek site 1c but partially exposed sections occur at the North Creek, S-surve, and Sevenmile Creek sites. The basal contact with the Pierre Formation is gradational; the upper contact with the hummocky-bedded facies is placed where hummocky bedding becomes dominant.

Massive component.--The massive component is heterolithic; it consists of a mottled mixture of light gray (N 7) silt and gray clay (fig. 25). Remnant, finely intercalated silt and clay beds prevail in the upper portion of the facies; bedding planes are gradational. No remnant bedding was observed at site 1d. At site 2d, the lower portion of the facies is composed mostly of silt but the upper half contains both interbedded and mixed silt and clay. No ichnofossils were observed but the mixed and mottled character of the sediment strongly suggests biogenic reworking. Mixed sandy-silt concretions may represent wholly reworked hummocky beds.

Hummocky component.--Two to three tabular hummocky beds (HbMb), 0.5 m thick and composed of light gray (N 7), very fine, sandy silt, occur in the upper portion of the facies at Little Beaver Creek (1c, 1d) (fig. 26). The beds have sharp basal contacts, are laterally

continuous in outcrop, and are bioturbated in their upper portions by Ophiomorpha nodosa and Cosmorhaphis. The hummocky L-sets of the H zone are small-scale (5 cm by 10 cm).

Hummocky-bedded facies







The tabular hummocky-bedded facies is typically 19 m thick in the thesis area (fig. 24). The basal contact is considered conformable since hummocky bedding occurs below in the massive-hummocky facies; the base of the hummocky-bedded facies is drawn where the hummocky beds become dominant in the section. The contact appears to be erosional only because the basal contact corresponds to the basal scour surface of the basal hummocky bed of the hummocky-bedded facies. The contacts between the subfacies are conformable. The upper contact is sharp and erosional. Within the facies, grain size and sand content increase upward; the sediment is moderately sorted and lateral variation in sorting is low.

Three subfacies (from the base)--lenticular, normal-bedded and amalgamated--can be delineated based on variations in the ideal internal sequence of the hummocky beds (fig. 14, 24, 27). The lenticular subfacies is replaced south of the Little Beaver Creek exposures by the lower portion of the normal-bedded subfacies. The normal-bedded subfacies and the overlying amalgamated subfacies occur throughout the study area. Only the planar wavy layers (W zones) break the massive appearance of the unit at the outcrop. The wavy layers (W zones) are rarely bioturbated.

Lenticular subfacies.—The lenticular subfacies is 2-3 m thick and was observed only at the Little Beaver Creek exposures (sites 1b, 1c). The subfacies is characterized by lenses composed of lenticular

Figure 24. Characteristics of the sedimentary structure facies of the lower Fox Hills Formation. Conformable contacts are labeled "C"; unconformable are labeled "U".

LEGEND

Wavy Bedding	
Wave Ripples	
Hummocky Stratification	
Finely Interbedded	
Mixed Bedding	
Hummocky Bed Interval (between first order surfaces)	

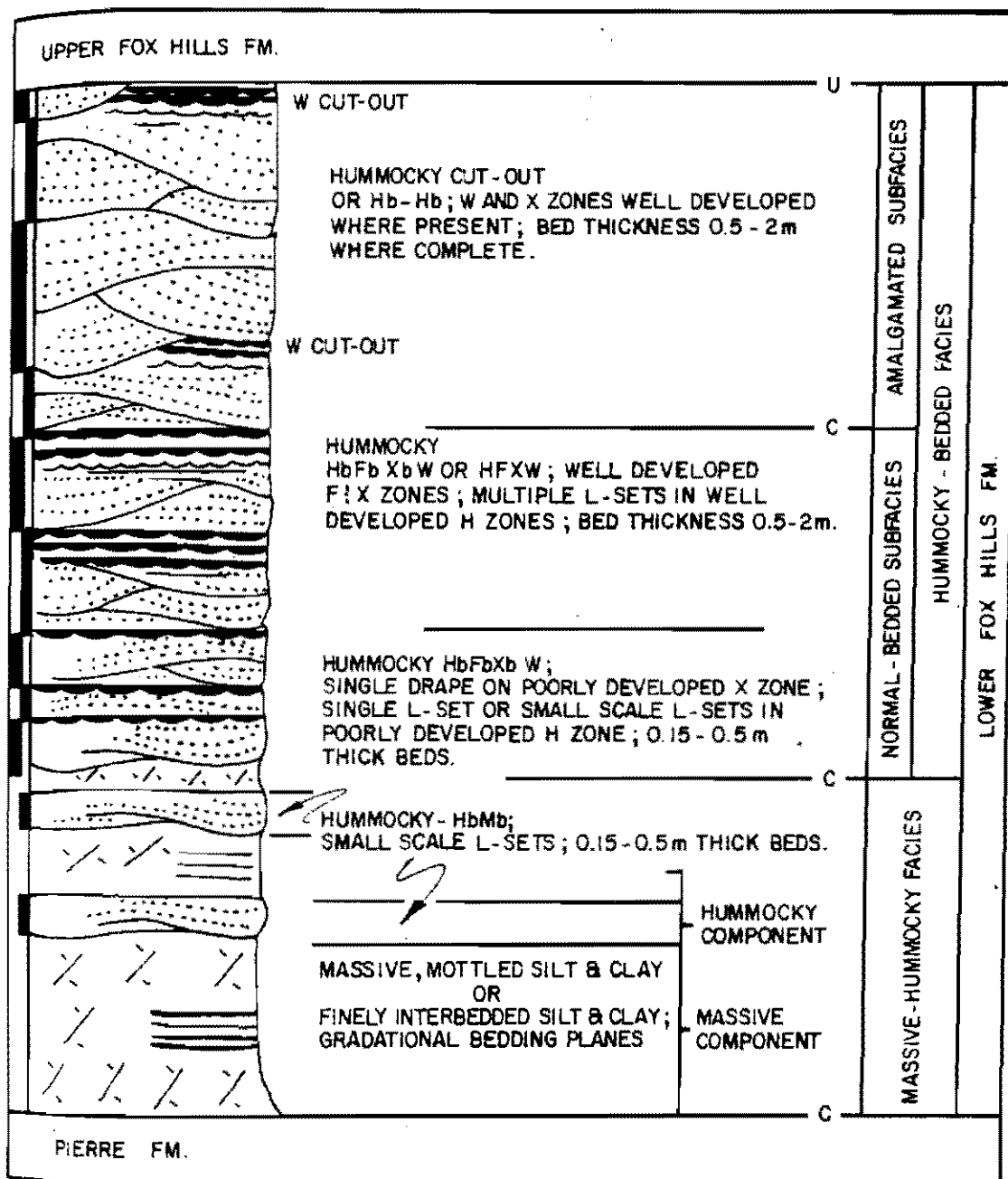


Figure 25. Bedding in the upper massive-hummocky facies. Interbeds of light gray silt (or sandy silt) and gray clay occur near the top of the facies at site 1a. Tape is 20 cm.

Figure 26. Hummocky component of the massive-hummocky facies. Multiple (?) hummocky beds comprise a tabular layer 0.4 m thick, in the upper portion of the facies at site 1a. The basal two thirds of the layer is bioturbated but some hummocky stratification survives. The uppermost bed (top 15 cm) is hummocky at the base but is overlain by mixed sediment containing Cosmorhaphe and O. nodosa, and unidentified fodinichnia.

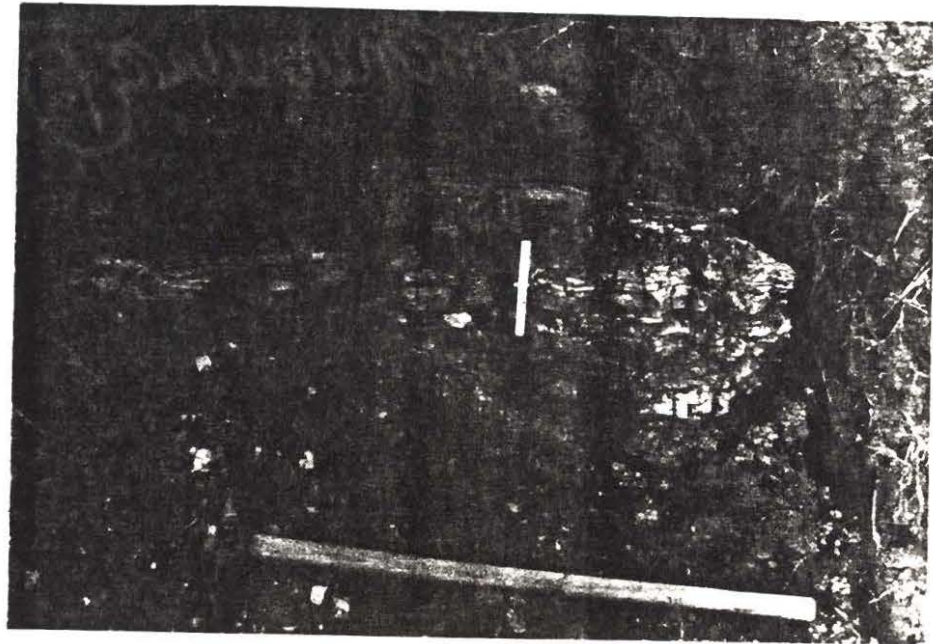


Figure 27. Characteristics of the lenticular subfacies of the lower Fox Hills Formation in the study area. The lenticular subfacies occurs between the massive-hummocky facies and the normal-bedded subfacies at the Little Beaver Creek outcrops (site 1) but does not occur to the south. The hummocky lentils merge upsection to form the base of the normal-bedded strata. Legend is on Figure 24. Conformable contacts are labeled "C"; unconformable are labeled "U".

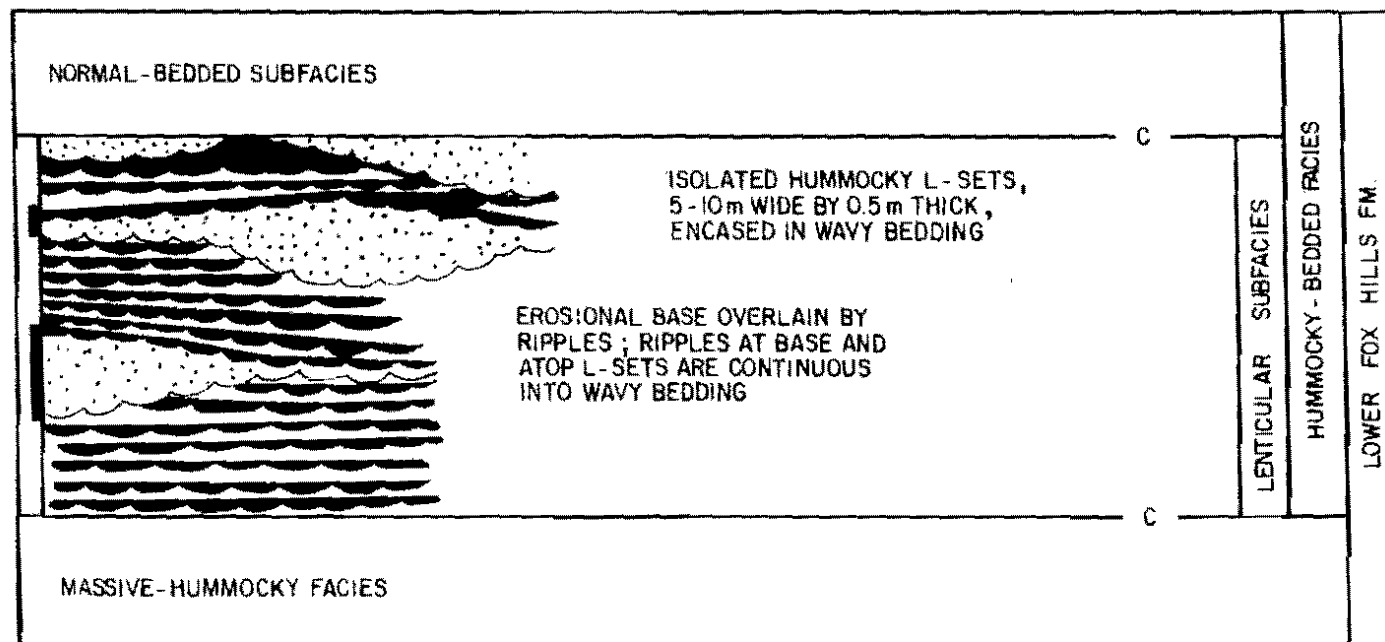
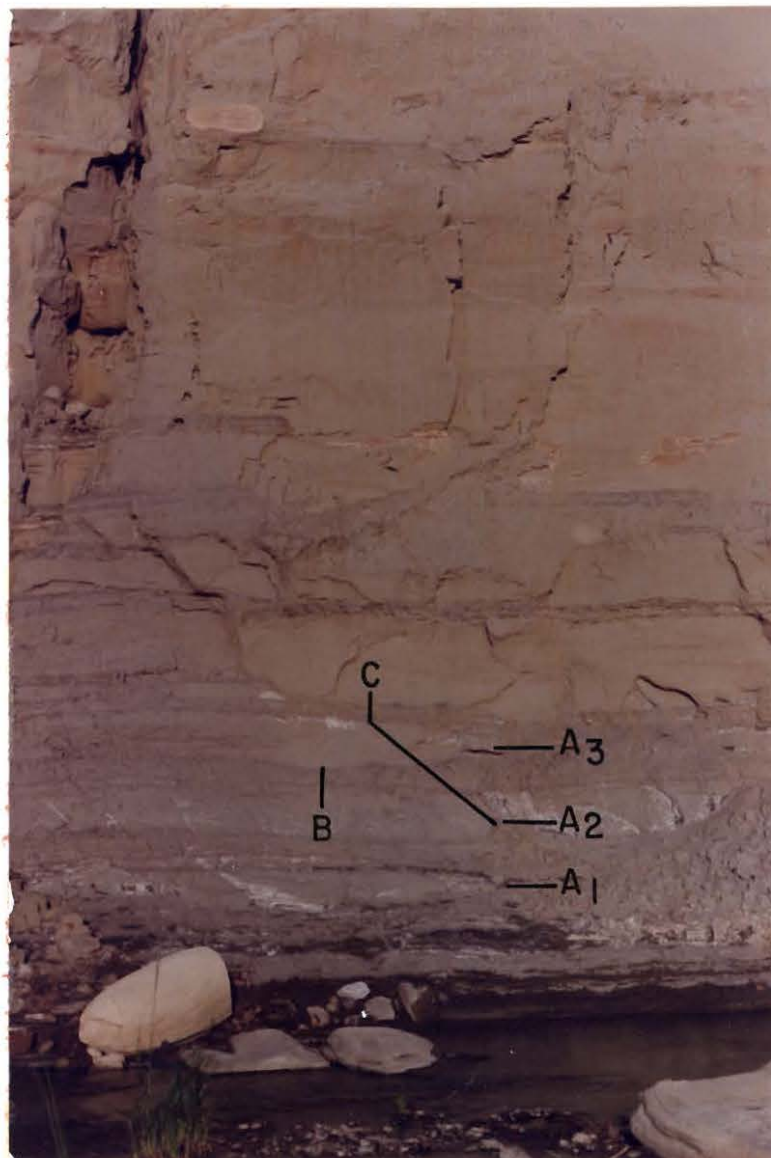


Figure 28. The lenticular subfacies of the lower Fox Hills Formation (site 1b). The hummocky L-sets at (A₁₋₃) are encased in wavy bedding; wavy layers are cut out at (C). A well developed ripple layer occurs at (B); wave ripples are continuous between the wavy and hummocky strata.

Figure 29. The upper portion of the normal-bedding subfacies of the lower Fox Hills (site 1b). Wavy layers occur at (A₁₋₃) as W zones atop hummocky (HFX) beds; a hummock at (B) is bounded by 2 swales. Pick is approximately 1 m.



hummocky beds containing a single L-set (HFX) distributed in wavy bedding; the lenses become more numerous near the top, finally coalescing, thereby forming normal-bedded hummocky sequences (fig. 27). No bioturbation was observed in this subfacies.

The L-set-lenses are 0.5 m high by 5-10 m wide; each has an erosional lower bounding surface and a gently sloping convex top (fig. 27, 28). Wave ripples occur along the lower bounding surfaces and overlie the lenses as an X zone; typically, the ripples are continuous with those in the adjacent wavy bedding.

Normal-bedded subfacies.--The normal-bedded subfacies is 10-15 m thick and is composed of muddy, very fine to fine sand; grain size and sand content increase upward (fig. 22, 23, 24). The upper contact with the amalgamated subfacies is placed atop the highest persistent W zone associated with normal hummocky bedding; the lower contact with the massive-hummocky facies is conformable and is placed where normal bedded units become stacked without intervening mixed zones.

The normal-bedded subfacies can be divided into upper and lower parts, both characterized by stacked, laterally continuous, layers. The major differences between the two parts are the scale and degree of development of the hummocky and wavy beds and the texture of the sediment (fig. 24). The contact between the parts is the scalloped basal scour of the hummocky beds of the upper portion; the contact is identified by a color difference from greenish gray (5GY 6/1) below to light olive gray (5Y 6/1) above.

The lower portion of the subfacies is 1-2 m thick in the northern exposures (Little Beaver and North Creeks) and 4-5 m thick in the south. The sediment is composed of greenish gray, very fine, sandy mud to muddy, moderately sorted sand (20 to 60 percent sand). The hummocky beds are 0.3 m thick; the W zones consist of a single gray clay drape, 1-2 cm thick, atop a poorly developed X zone. The hummocky beds are intensely bioturbated with Ophiomorpha nodosa producing HbFbXbW sequences.

The upper portion of the subfacies is 8 m thick. The sediment is composed of light olive gray, muddy, moderately sorted, very fine to fine sand (50-80 percent sand). Each HFXW bed is 1-5.3 m thick. The L-sets of the hummocky zone average 1-2 m wide and 0.5 m thick. Exceptional L-sets, 2 m thick and over 6 m wide were observed at the S-curve exposures (site 5b); a fully preserved hummock-swale configuration 1 m thick and 10 m wide was observed at the Little Beaver Creek exposure (fig. 29; site 1b). Rare, isolated Ophiomorpha nodosa were observed in the muddy, very fine sand of the H zones; few well defined zones of bioturbation were observed.

Amalgamated subfacies.—The amalgamated subfacies is 7-11 m thick and is composed of light olive gray, muddy, moderately sorted, fine sand (75-90 percent sand) that often weathers to moderate yellowish orange (10YR 6/6).

The amalgamated subfacies is characterized by Hb or W cut-out types of hummocky bedding (fig. 24). The general lack of preserved W zones (F and X as well) results in a sequence of hummocky zones that form an apparently massive unit. The bed contacts can be

inferred from the few surviving W zones or the distribution of Ophiomorpha borneensis bioturbation zones. The individual L-sets are 0.3 m thick and 1-2 m wide; few complete L-sets were observed.

Cross-bedded facies





The cross-bedded facies (fig. 14) is composed of light olive gray (5Y 6/1), moderately to poorly sorted, muddy, very fine to medium sand (70-85 percent sand). The facies is 6-9 m thick but may be as little as 2-4 m thick where major erosion from the overlying Hell Creek occurs. The basal contact is planar and erosional; the upper contact is erosional with varying amounts of erosion. Trough and epsilon cross-bedding are restricted to this facies. Several variations in bedding sequence occur within the study area (fig. 30).

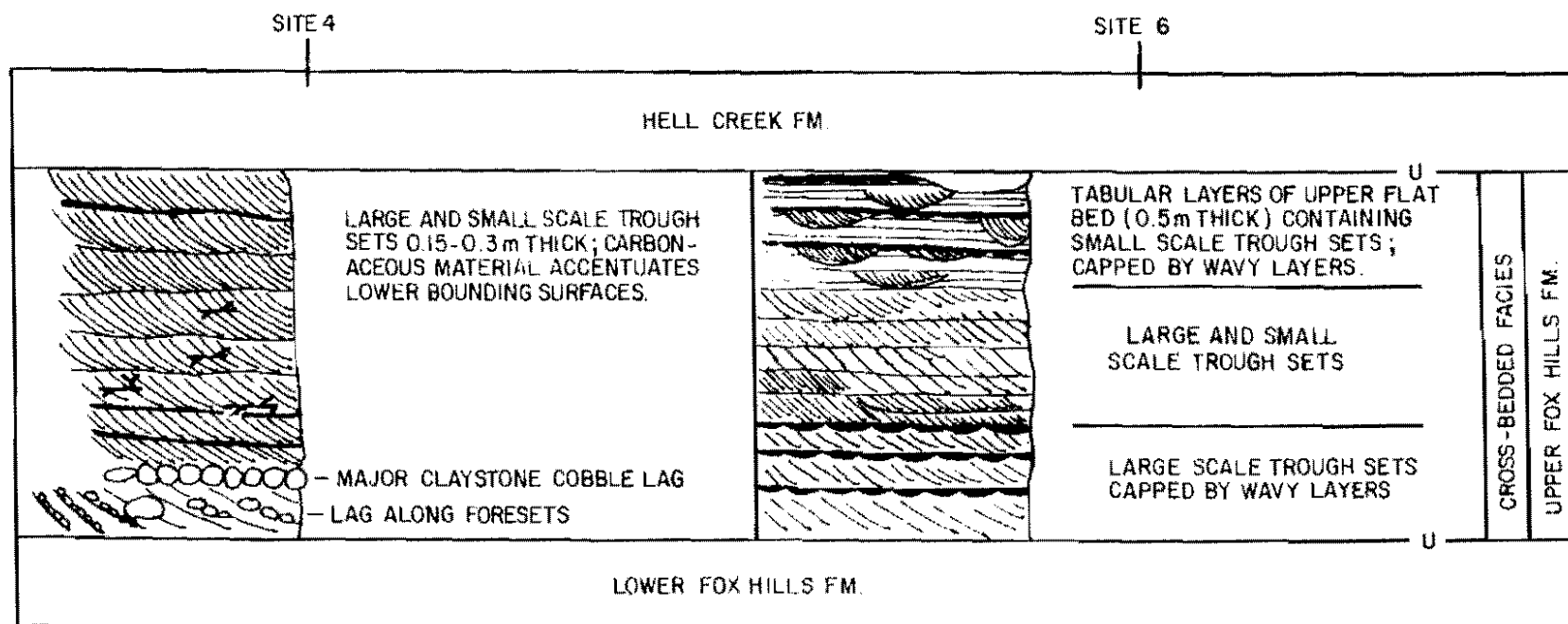
At site 4, the facies is characterized by large scale trough cosets (fig. 30, 31). The individual sets are 0.15-0.3 m thick and 2-3 m wide. In transverse section, the lower bounding surfaces are broadly curved and non-parallel; in longitudinal section the sets have parallel to subparallel lower bounding surfaces and contain tangential laminae. Carbonaceous material, concentrated at the toe of the laminae, serves to accentuate the lower bounding surfaces. Foreset dip directions are consistent to the south. A laterally continuous mudstone cobble lag occurs at the base, and rare, isolated Ophiomorpha borneensis occur in the trough sets.

At site 1a (fig. 32), the facies contains trough bedding at the base. Overlying the troughs, for 100 m along the outcrop, is a 4-m-thick set of epsilon cross-bedding. The foresets are accentuated by clay pebbles and carbonaceous drapes; the foreset contacts are

Figure 30. Characteristics of the cross-bedded facies of the upper Fox Hills in the study area. The section at site 4 consists mainly of trough cosets; the section at site 6 (also 2 and 7a) contains wavy layers in association with large scale troughs at the base and atop "scour and fill" beds in the upper portion.

LEGEND

Scour and Fill Bedding	
Trough Cross- Bedding	
Wavy Layer	
Lag	
Unconformity	U



tangential with the erosional lower bounding surface.

At the majority of outcrops (2b, 2c, 6 and 7a; fig. 30, 33-37), the facies is characterized by (from the base): medium-to large-scale trough sets or cosets each overlain by a wavy layer (fig. 34); medium-scale tabular trough sets (fig. 32); and tabular, 0.3-0.5-m-thick layers containing isolated scoop-shaped or tabular medium-to small-scale troughs in horizontal lamination (fig. 35, 36, 37), a variety of scour and fill bedding. The scour and fill beds are capped by wavy layers, laminae discordances, or erosional ripples.

The trough sets associated with the horizontal lamination in the scour and fill bedding are characterized in the following way (fig. 35): (1) the sets at 6-10 cm thick x 1-3 m long (sets may be up to 16 cm thick and 8 m long); (2) the lower bounding surface is erosional, planar and near horizontal in longitudinal section; in transverse section the bounding surface is a shallow broad trough (transverse views were rare); (3) the sets are isolated, usually separated by 8-10 cm from the overlying trough horizon and bounded in their own horizon by horizontal laminae; (4) the set laminae are tangential to sigmoidal and are continuous with the horizontal laminae at the downstream end of the trough set; (5) each trough horizon exhibits a uniform foreset drip direction but opposing directions can occur at a single outcrop.

Figure 31. Sedimentary structures in the cross-bedded facies (site 4a). Claystone cobble and pebble lag (A) underlies large scale trough cosets (similar to those in fig. 11, 12). Small scale trough sets below, are interspersed with claystone pebble lags. The strata are interpreted as a channel deposit (p. 175). The glove is 10 cm wide.

Figure 32. Epsilon cross-bedding (A) occurs atop trough cross-bedding (B) in the upper Fox Hills (A-B). The epsilon cross-bedding is interpreted as a channel point bar (p. 175). The Little Beaver Creek Member of the Hell Creek Formation overlies A; the hummocky bedded facies of the lower Fox Hills Formation underlies (B). From the level of Little Beaver Creek to B is 10 m. Photo at site 1a.



Figure 33. The middle third of the cross-bedded facies (site 2b). This view overlies that in figure 34. Wavy layers occur at (A₁-2). Interval (A₁-A₂) contains trough beds 15-20 cm thick and characterized by even, erosional bounding surfaces. Foreset dips are consistent to the west (right). The strata are interpreted as shoreface deposits (p. 174). Similar structures occur at sites 6f and 2c. Pick is approximately 1 m.

Figure 34. The basal portion of the cross-bedded facies (site 2b). Wavy layers, wave (?) ripples overlain by carbonaceous or micaceous drapes (A₁-5), cap trough cross-beds; intermittent high energy conditions are indicated. The strata are interpreted as shoreface deposits (p. 174). Fluting is well developed. Tape is 0.6 m.

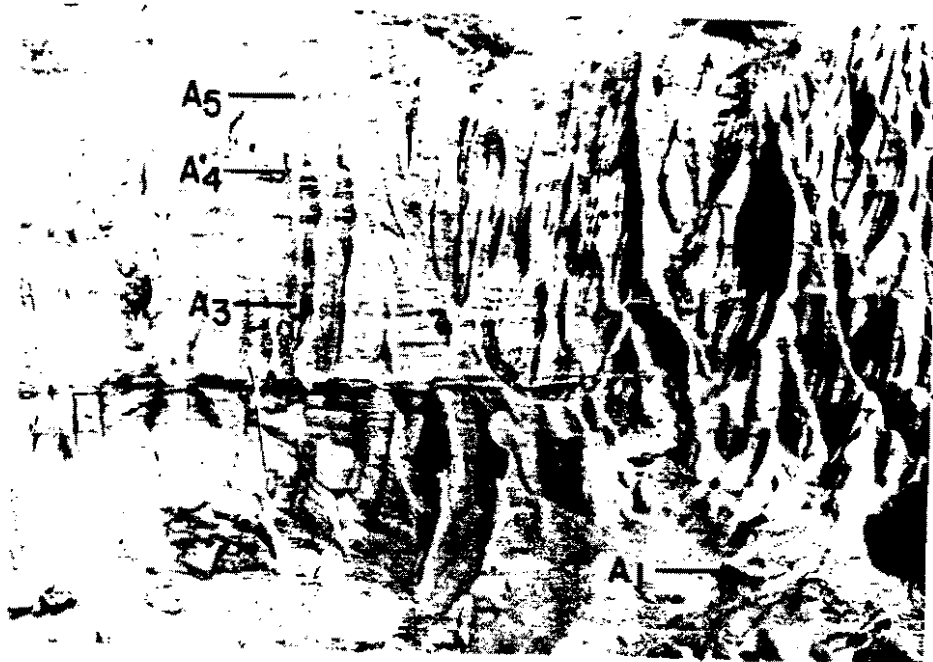
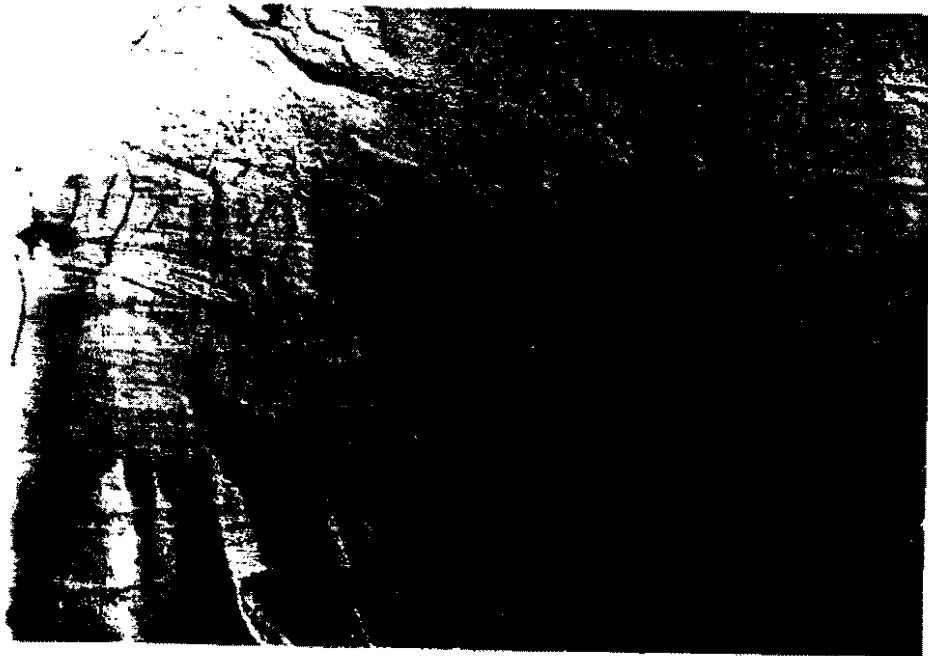


Figure 35. Sedimentary structures in the cross-bedded facies (site 6e). Small scale trough sets occur associated with horizontal laminae (scour and fill bedding). Erosional ripples occur at (A_1 and A_2). Similar structures occur at site 7a and in the upper portion of the facies at 6d. The features represent high energy conditions and are interpreted as shoreface deposits (p. 174). Scale is 15 cm.

Figure 36. Sedimentary structures in the cross-bedded facies (site 6e). Small scale trough sets occur associated with horizontal laminae (scour and fill bedding). Erosional ripples occur at (A). Similar structures occur at site 7a and in the upper portion of the facies at 6d. The features represent high energy conditions and are interpreted as shoreface deposits (p. 174). Scale is 15 cm.

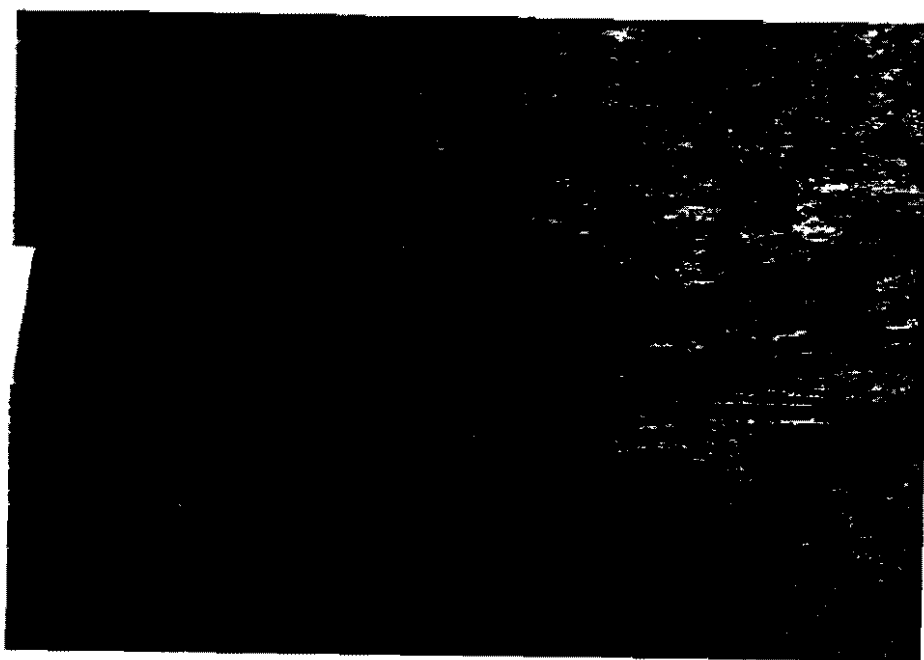


Figure 37. Sedimentary structures in the cross-bedded facies (site 6d). In the sequence A-D: the basal 2 m (A-C) is composed of large scale trough beds separated at (B) by a locally persistent wavy layer, and wavy layers occur atop trough sets in (A-B); the upper half of the sequence (C-D) is composed of 0.3-m-thick scour and fill beds containing small scale troughs and horizontal lamination capped by wavy layers. A root zone occurs at (D). The sequence is interpreted as a shoreface deposit (p. 175). The pick is approximately 1 m.



STRATIGRAPHY

Formation Definition

The Fox Hills Formation of the study area is a tabular unit, typically 37 m thick, that consists of two parts (fig. 3, 5, 38, 39): a 10-m-thick basal silt-clay unit (massive-hummocky facies) here included as a part of the study-area Fox Hills for the first time, and an overlying sand unit (hummocky-bedded and cross-bedded facies), 27 m thick, that represents the formation as it had previously been defined in the study area. The Pierre-Fox Hills contact is here placed 10 m lower in the section, at the base of the massive-hummocky facies; the Fox Hills-Hell Creek contact has not been redefined.

The formation, as here defined, is composed of three members (from the base; fig. 3, 5, 38, 39)--Trail City, Timber Lake, and Colgate--that correspond to the sedimentary structure facies. The Trail City Member is the name here assigned to the basal silt-clay unit (massive-hummocky facies); this name has not previously been formally applied in the area of the Cedar Creek anticline. The formation can be divided into lower (Trail City, Timber Lake) and upper (Colgate) Fox Hills. A detailed picture of the stratigraphy in the study area is provided by the measured sections in Appendix A, part 2.

Marker Zones

Six local marker zones were recognized in the section; these

Figure 38. The stratigraphy of the Fox Hills Formation in the study area.

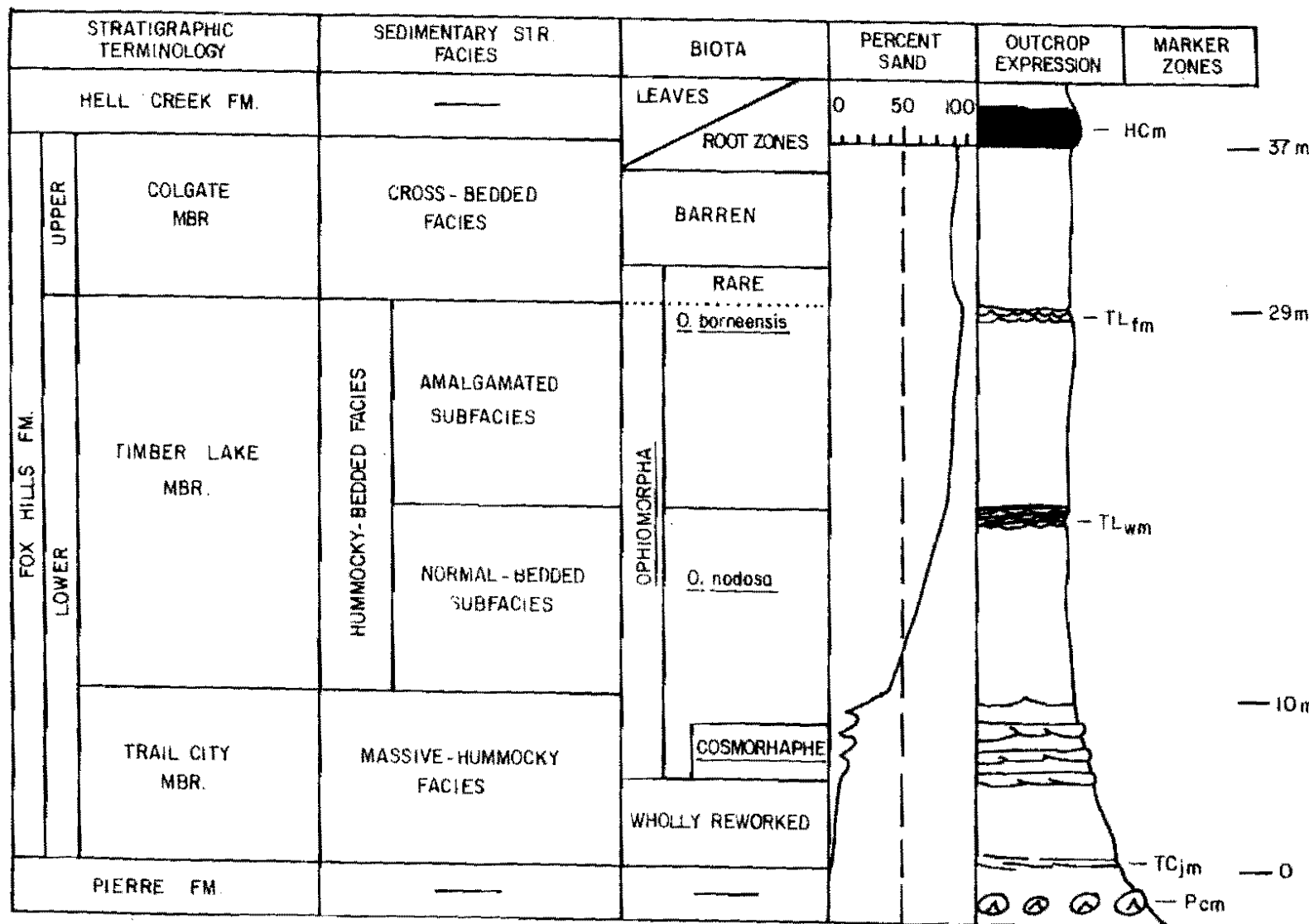












Figure 39. Stratigraphic cross-section of the Fox Hills in the study area.

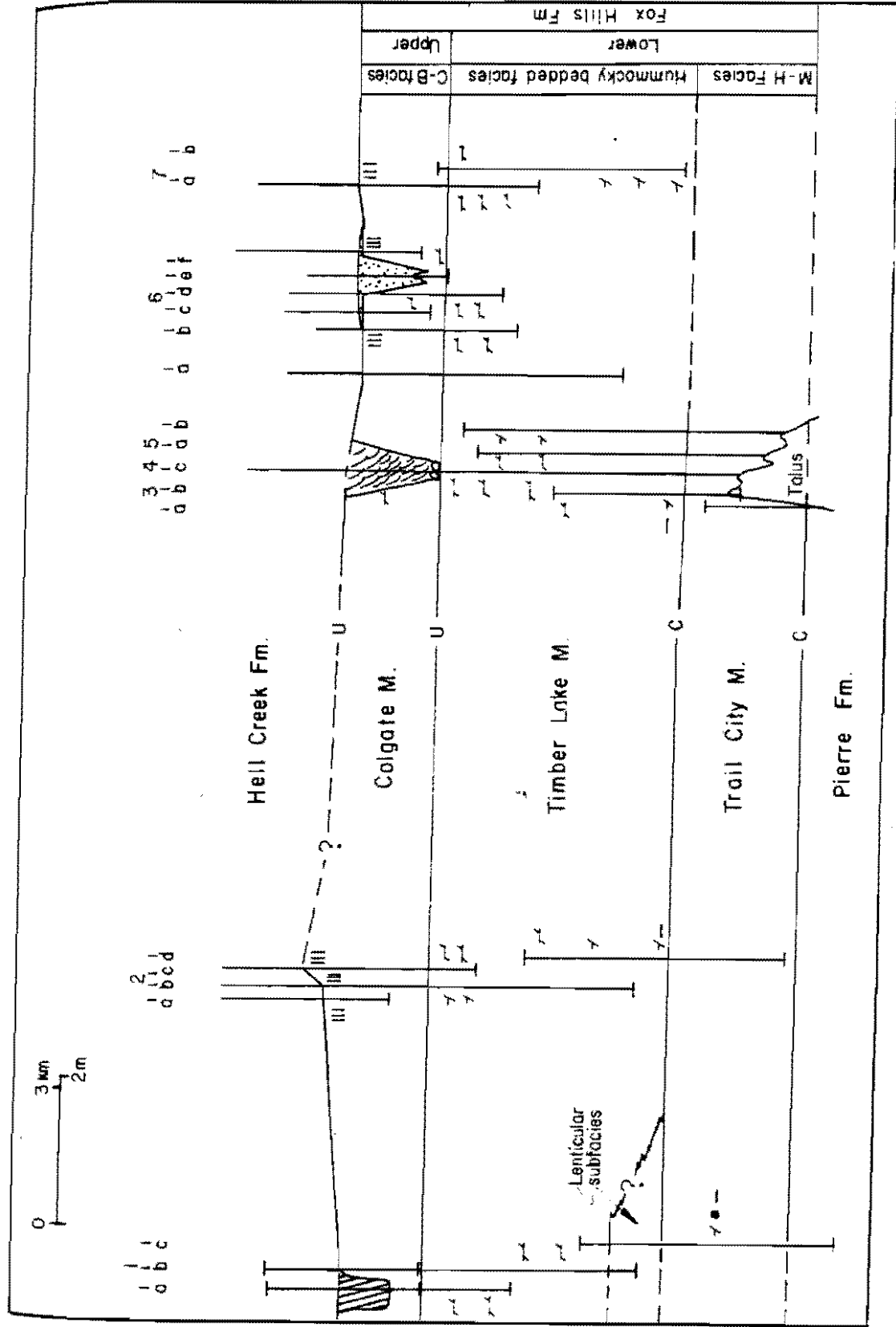
LEGEND

Trace fossils

<u>O. borneensis</u>	
<u>O. nodosa</u>	
Fodinichnia	
<u>Cosmorhaphe</u>	
Root Molds	

Structures

Channel	
Point bar	
Hell Creek erosion	
Unconformity	
Conformable contact	



are labeled with the capital letter of the member or formation they occur in, followed by a small letter "m" (fig. 38).

Pcm.--The Pierre cone-in-cone layer marks the highest occurrence of cone-in-cone concretions in the Pierre Formation. The concretions average 20 cm in diameter and exhibit cone-in-cone structure throughout. The marker was observed at sites 1c and 3a. The Pierre Fox Hills contact typically occurs 1-3 m above this zone.

TCjm.--The Trail City jarosite marker (fig. 40) is composed of moderate yellow (5Y 7/6), jarosite-impregnated-silt interbedded with gray clay. The zone is 1.5 m thick at site 1c but is poorly defined at site 3c. The base of the TCjm coincides with the Pierre-Fox Hills contact.

TLcm.--The Timber Lake concretion marker (fig. 41) is characterized by a zone of spherical to elliptical, massive, very fine sandy silt concretions; diameters average 0.3-0.5 m. The base of the zone marks the top of the Trail City Member (massive-hummocky facies) and the base of the Timber Lake Member (hummocky bedded facies). The zone was observed at all outcrops where that portion of the section was exposed. The zone represents a partly mixed hummocky bed as evidenced by remnant hummocky stratification.

TLwm.--The Timber Lake wavy marker is the highest occurrence of a substantial wavy bedded layer (W zone) associated with normal-bedded strata. The thickness of this marker ranges from 0.15 m (site 1b) to 0.3 m (site 2a) to 1.2 m in the southern outcrops. The zone proves helpful at the majority of outcrops where only the upper portion of the hummocky-bedded facies is exposed. This

marker is planar, and may be laterally continuous for 0.5 km.

TLfm.--The Timber Lake ferruginous marker (fig. 42) consists of a planar, ferruginous; wavy layer or bed; the top of this marker corresponds to the top of the Timber Lake Member, the hummocky-bedded facies, and typically the highest occurrence of zones of Ophiomorpha borneensis bioturbation.

The character of this marker varies as follows: at site 7a, the marker is 0.3 m thick, laterally discontinuous, and consists of current ripple-claystone wavy bedding; at sites 6b-d, the marker is 1.2 m thick, contains draped trough-bedding, and is laterally continuous for 0.6 km; and at the site 4a-c, the zone is 0.75 m thick, consists of wavy bedding, and is laterally continuous for 0.5 km.

HCm.--The Hell Creek marker (fig. 45) occurs at the base of the Little Beaver Creek Member of the Hell Creek and consists of indurated dark yellow brown (10YR 4/2), carbonaceous, muddy, fine to medium sand that may be massive (sites 1, 2, 7a) or exhibits trough-bedding (sites 6b, 6c, 6d, 7a). The HCm is typically 1 m thick but may be thin or absent (site 2b, 4, 6c-d). The base of this marker has long been considered the Fox Hills-Hell Creek contact (Feldmann 1967, 1972; Frye 1969; Carlson 1979).

Pierre-Fox Hills Contact

Pierre Formation.--The Pierre Formation is typically composed of gray, massive clay or silty clay, exhibits a blocky fracture, and weathers to a dark gray (N3 or N4); the surface of Pierre outcrops is

Figure 40. The Trail City jarosite marker (TCjm). The marker is composed of moderate yellow (5Y 7/6) jarosite-impregnated-silt interbedded with gray clay. The scale is 15 cm. Photo from site 1c.

Figure 41. The Timber Lake concretion marker (TLcm). The base of the TLcm marks the Trail City-Timber Lake contact. The marker consists of a partly bioturbated hummocky bed; O. nodosa occurs at (A). The card is 5 cm wide. Photo from site 2d.

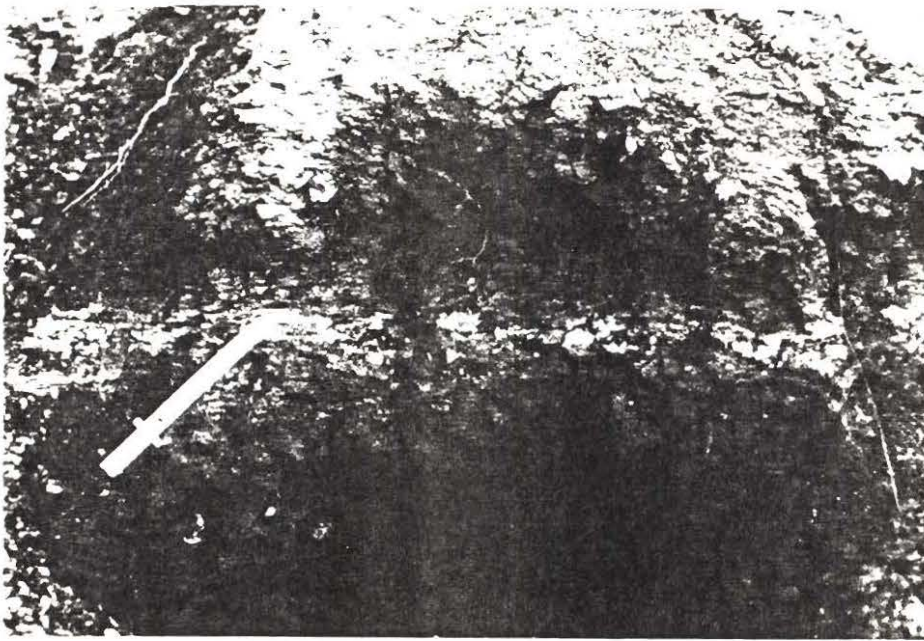
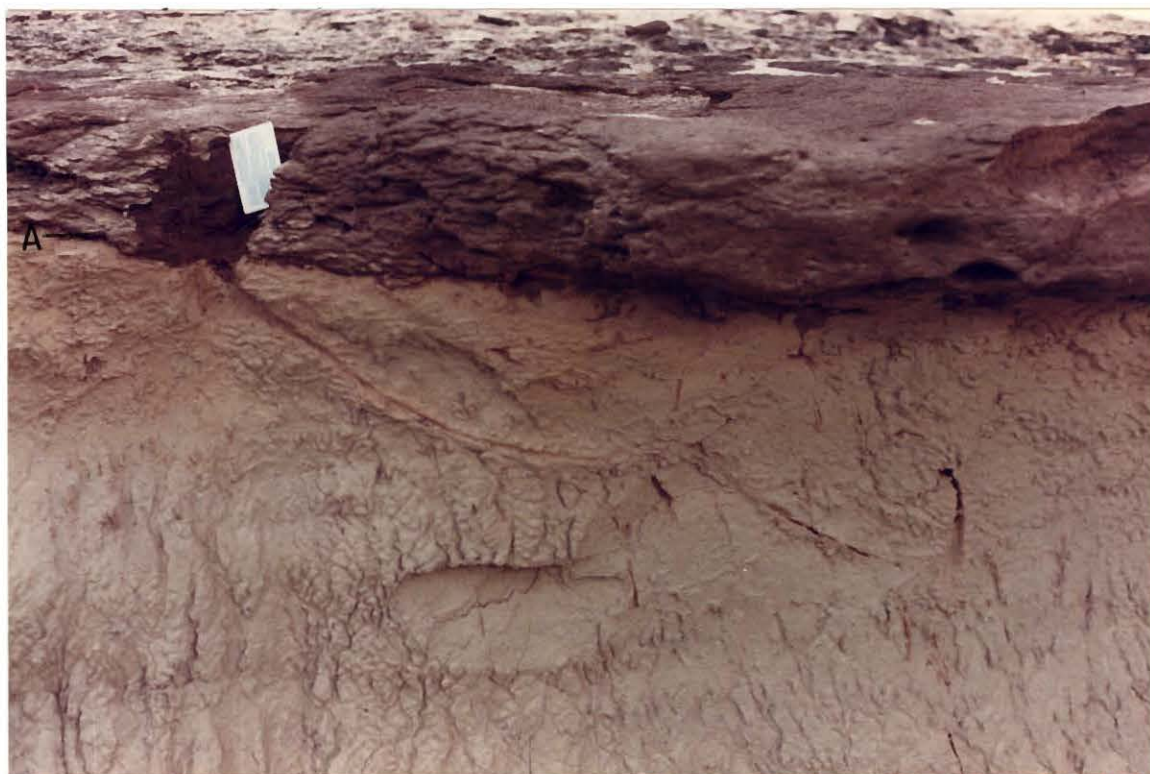


Figure 42. The Timber Lake ferruginous marker (TLfm). The top of the TLfm (A) marks the Timber Lake-Colgate contact; the tiered galleries of O. borneensis appearing as raised irregularities are common in the amalgamated subfacies of the upper Timber Lake Member. The pick is approximately 1 m. Photo from site 6e.

Figure 43. The Hell Creek marker (HCm). The Fox Hills-Hell Creek contact has traditionally been placed at the base of the carbonaceous HCm (A). The upper 2 m of the underlying Colgate contains root molds; the roots are not from the overlying HCm. Leaves often occur in the vicinity of the contact. The HCm is typically composed of carbonaceous, muddy sand; the unit may contain trough foresets or may contain irregular bedding planes. The layer is indurated, typically forming benches. The card is 5 cm wide. Photo from site 2a.



covered with indurated shale "chips" and translucent selenite crystals. The Pierre forms rounded, gentle slopes, is slick when wet, and is characterized by dendritic drainage.

The clay of the Pierre becomes more silty upward and contains thin silt stringers in the top 10 m. A layer of cone-in-cone concretions (Pcm zone) occurs 1-3 m below the contact. Ovoid siltstone concretions, rich in ammonites and other body fossils, that occur 3-5 m below the contact in the Glendive area (Bishop 1973), were not observed in the Pierre of the study area.

Contact definition.--The Pierre-Fox Hills contact is placed at the horizon where the monotonous, gray clay of the Pierre is replaced upsection by the mottled, mixed, light gray (N7) silt and gray clay or the thinly intercalated, silt-clay of the massive-hummocky facies (Trail City Member). The light gray (N7) color of the massive-hummocky facies is quite similar to the dark gray of the Pierre. Where the contact is exposed (sites 1c, 3c), a definite break in slope, and the coincident TCjm, mark the contact. Elsewhere, stream beds occupy the level of the contact, or the contact is buried beneath considerable talus.

The contact, as here defined, represents a departure from the traditional practice in the study area; the basal contact had been placed at the base of the lowest sand in the section (base of the hummocky-bedded facies) since the work of Stanton (1910) (fig. 5, 38). This early practice had been continued in this area as a result of the persistence of the early "Rocky Mountain" definition of the Fox

Hills (Stanton 1910; elucidated by Waage 1968, p. 36), the belief that no Trail City Member was present in North Dakota (Waage 1961, 1968; Feldmann 1967, 1972), and most importantly, the small number and poor quality of both the exposures of the massive-hummocky facies and the contact interval. Although many workers have investigated the spectacular outcrops of the hummocky-bedded facies on Little Beaver Creek (sites 1a, 1b), none reported visiting the gentle slopes on the creek 3 km to the south (site 1c) where the contact, as here defined, is exposed.

Waage (1968, p. 60-61) stated that the basal contact should be placed at the horizon where silt becomes predominant in the section. The placement of the contact in the study area reflects a change in lithology (clay changing upsection to silt and clay), sedimentary structures (lack of structures changing upsection to mixed or thinly interbedded), and, secondarily, a change in faunal occurrence (lack of fauna changing upsection to plentiful). The placement of the contact, as here defined, is in agreement with the criteria used by Waage (1968) in the type area, Erickson (1971) in the Missouri Valley of North Dakota, Calvert (1912) and subsequent workers, notably Bishop (1973) and Wilde (1983), in the Glendive area, and Jensen and Varnes (1964) in the area of Fort Peck, Montana.

Fox Hills-Hell Creek Contact

Hell Creek Formation.--The Little Beaver Creek Member of the Hell Creek Formation overlies the Fox Hills Formation in the thesis area (Frye 1969, p. 20-21, 61-63). The strata typically consist of 10-12 m

of tabular, interbedded claystone and mudstone layers 15 cm- 0.5 m thick that contain root molds and leaf hash; minor sands occur. This member is overlain by the medium sand and large scale trough cross-beds of the Marmarth Member (Appendix A, part 2). The typical colors are browns and grays; bentonitic beds are common (fig. 44). Individual beds cannot be traced laterally for any distance.

Contact definition.--The contact occurs between the Little Beaver Creek Member of the Hell Creek Formation and the underlying Colgate Member (cross-bedded facies) of the Fox Hills Formation. The contact as here defined is the same as that delineated by Feldmann (1967; 1972), Frye (1967, 1969) and Carlson (1979) in the study area (fig. 5, 38).

The contact is typically unconformable but the significance of the unconformity is probably minor. At most outcrops (sites 1, 2, 6, 7), the upper 2 m of the Colgate consists of light olive gray, fine-medium, muddy sand (70-85 percent sand) that contains root molds. The upper surface of the member is scoured into broad, shallow troughs (1-2 m relief) that are overlain by the carbonaceous sand of the HCm (fig. 45, 46).

However, at site 6e, the HCm is locally absent and the contact is an irregular surface with major relief (3-6 m); the upper half of the Colgate, including the root zone, has been cut out by erosion. The contact is between the light olive gray fine sand, arranged in scour and fill beds (Colgate Member), below and the large scale longitudinal and torrential cross-bedding of the Little Beaver Creek Member above.

Figure 44. Hell Creek Formation (Little Beaver Creek Member, site 6f). In the lower half of the photo epsilon cross-bedding is overlain by a bentonitic bed; the epsilon set is 4 m thick.



Figure 45. The Fox Hills-Hell Creek contact (site 2a). The contact (A) occurs between the Colgate Member and the overlying HCM (basal bed of the Little Beaver Creek Member). The contact is characterized by minor erosion; the HCM contains very angle foresets in broad, shallow troughs. A wavy layer occurs in the Colgate at (B) overlain by large-scale trough bedding. Structures in the upper 0.5 m of the Colgate are obscured by root molds. The Colgate section is 2.8 m thick.

Figure 46. The Fox Hills-Hell Creek contact (site 6d). The contact (A) occurs between: the Colgate and the overlying HCM (basal bed of the Little Beaver Creek Member). The contact is characterized by 1-3 m of relief. The carbonaceous HCM contains low angle foresets (epsilon bedding ?). The lower surface of the HCM is variable but the upper surface is typically horizontal. The overlying Hell Creek is characterized by interbedded clays, silts, muds, and carbonaceous sands that often contain root molds and leaf concentrations. The sedimentary structures for the Colgate are described on Figure 37. The Colgate section is 4 to 5 m thick.

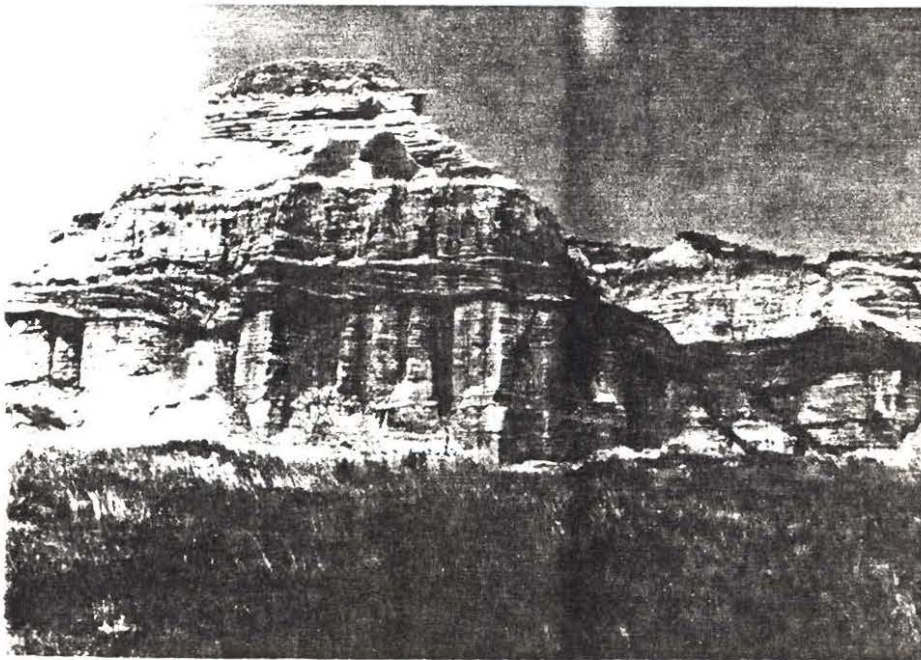


Figure 47. The Fox Hills-Hell Creek contact (site 2b). The contact (A) occurs at the base of a carbonaceous bed (Little Beaver Creek Member) overlying the Colgate; the HCm is absent at this site. The drapes above the contact are bentonitic. Wavy layers occur in the strata of both formations; relief on the contact is minor. The pick is approximately 1 m.



Where the HCM is poorly developed or absent without major erosion (sites 2c and 4), the contact was chosen where the light olive gray sand of the Colgate was replaced by gray bentonitic clay and minor carbonaceous beds (fig. 46).

Member Definitions

Trail City Member

The Trail City Member (massive-hummocky facies; fig. 38) contains: mottled, mixed and finely interbedded silt-clay strata (massive component); and two or three tabular, very fine sandy hummocky beds containing O. nodosa, Cosmorhappe, and various fodinichnia (hummocky component). The silt and sandy mud are light gray (N 7); the clays are medium gray (N 5). On weathered surfaces, the sediment is light to medium gray, but the colors are typically obscured by lighter colored slopewash.

The member is tabular and 10 m thick. The gradational Pierre-Fox Hills (Trail City) contact is marked by: a surface color difference of dark gray to light gray (N 7); a steepening of slope; and the presence of the TCjm. All of these manifestations occur 2-3 m above the Pcm. The Trail City-Timber Lake contact is placed along the basal hummocky scour of the hummocky-bedded facies; no major break in sedimentation is evident. The upper contact is placed at the base of the Tlm.

The texture and sedimentary structures of the Trail City in the study area are similar to those in the type area, and most closely resemble the strata of the Little Eagle lithofacies. At the type

locale of that lithofacies (loc. 6, fig. 1, 3) I observed several tabular, 0.3-0.5-m-thick, hummocky beds that were interbedded with mixed silt-clay and fossiliferous concretions; these layers, according to Waage (1968, p. 63, 85, units 5, 7, 10), exhibited "cross lamination". The fossiliferous concretions of the type locale are, however, absent from the study area exposures.

Timber Lake Member

The Timber Lake Member (hummocky-bedded facies; fig. 38, 48, 49, 50) is composed of sublithic or subarkosic sandy muds to muddy sands that become coarser upsection: in the lower part of the member (normal-bedded subfacies), the sand changes upsection from greenish gray (5GY 6/1), moderately sorted, very fine, sandy mud (20-60 percent sand) to light olive gray (5Y 6/1), moderately sorted, muddy, very fine to fine sand (50-80 percent sand); the upper portion (amalgamated subfacies) contains moderately sorted, muddy, very fine to fine sand (75-90 percent sand). Weathered surfaces, especially along wavy layers, have a ferruginous orange color. The member is further characterized by L-set-form concretions and secondarily by zones of Ophiomorpha nodosa at the base and Ophiomorpha borneensis at the top.

The member is tabular and 19-22 m thick (fig. 39). The normal-bedded subfacies is 10-15 m thick; the amalgamated subfacies is 7-11 m thick. At the Little Beaver Creek exposures (sites 1b, 1c), the normal-bedded subfacies is 5 m thick; the underlying lenticular subfacies, 3 m thick, forms the base of the member, and grades up

Figure 48. The Trail City-Timber Lake contact (site 2d). The contact (A) is placed at the base of the TLcm. Previously, the horizon 1 m above the TLcm, marked by the color difference, has been defined as the Pierre-Fox Hills contact. The interbedded silt-clay of the Trail City occurs below (A); the muddy sand of the lower normal-bedded facies occurs above. Several ferruginous W zones occur in the Timber Lake. O. nodosa occurs in the TLcm and in the hummocky strata above. Compare with Feldmann (1972, fig. 4), and Carlson (1979, fig. 6). Seven meters of Timber Lake is shown in the photo.

Figure 49. The lower Fox Hills Formation (site 5b). The Trail City-Timber Lake contact, marked by the TLcm, occurs at (A). In the Timber Lake (hummocky-bedded facies), the lower-upper normal bedded facies contact occurs at the color change (B); the contact with the amalgamated facies is at the top of the TLwm at (C). Hummocky surfaces are preserved by the drape at (D); hummocky concretions occur at (E). O. nodosa occurs throughout the normal-bedded subfacies. The normal bedded subfacies (A-C) is 12 m thick.



Figure 50. The Timber Lake Member (site 7b). The lower-upper normal-bedded subfacies contact is at (A); the contact with the amalgamated facies is atop the TLwm at (B). The contact with the adjacent members is not visible. Both (B) and (C) mark wavy bedding; ferruginous W zones (D) are cut out. O. nodosa occurs in the normal bedded sub-facies; O. borneensis occurs in the amalgamated facies. The interval (A-B) is 10 m thick.

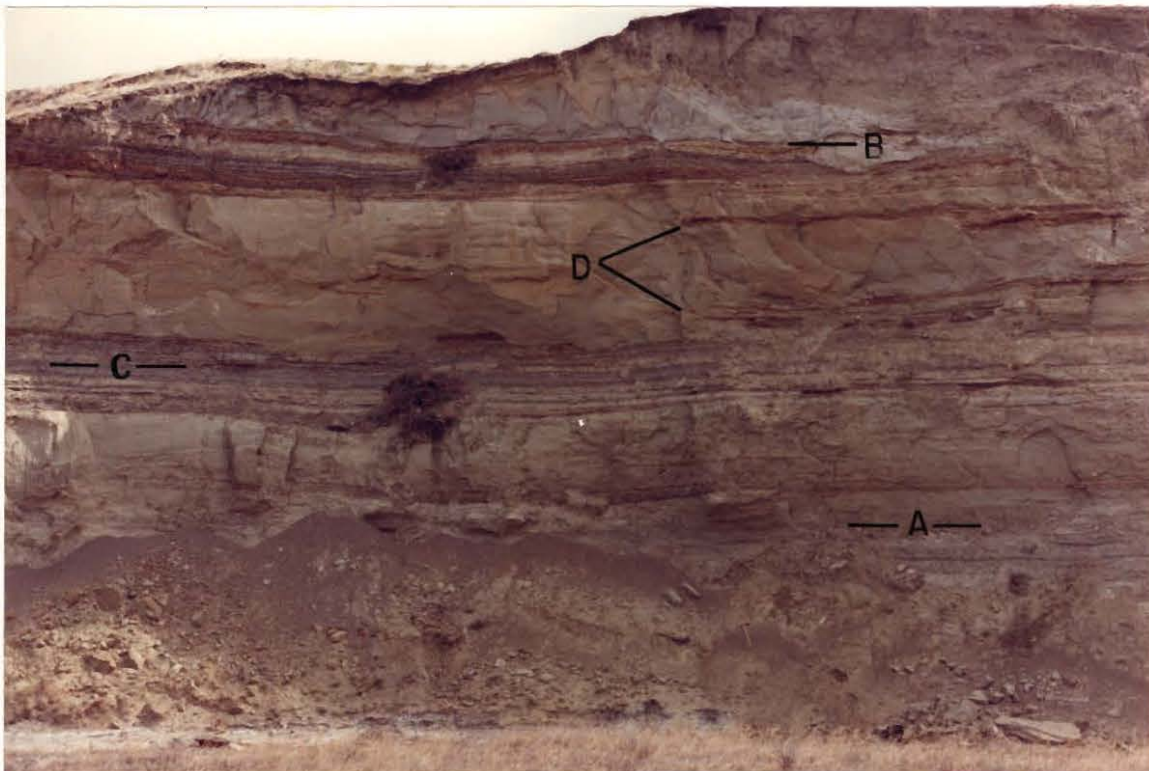


Figure 51. Summary of petrologic characteristics of the sand portion of the Fox Hills Formation along the south rim of the Williston Basin. The sands of the southeast rim are rich in volcanic rock fragments and contain layers of bentonite; the sands in the west contain neither. The Linton Member is designated by "L.M.". The Colgate, unlike the adjacent strata, appears to be devoid of volcanic fragments regionally thereby suggesting a possible means of recognition in the subsurface.

	Sand % and grain size	% Quartz	% Feldspar	Rock Fragments		Remarks	Investigation	
				%	Type, %			
Colgate Member	90; fine-medium	55 - 75	> 5	Up to 45	70 (chert)	No volcanic ash; minor volcanic rock fragments; minor matrix	Butler (1980)	Southwest Rim
	30	most abundant	minor	-	metamorphic quartzite chert shale	No volcanic ash; matrix clay (beidellite, kaolinite) from detrital grains	Ross in Dabbin & Reeside (1929) Montana area	
	70-85; fine-medium	70-85	10-20	10-20	mainly chert	No volcanic ash; very minor volcanic rock fragments; matrix clay (illite) from detrital grains	<u>This study</u>	
	35-55	-	-	-	-	No volcanic shards	Klett and Erickson (1976)	Southeast Rim
	30-50; fine-medium	50	-	50	quartzite foliated chert	Mico and feldspar accessories; siliceous and clay matrix	Waage (1968)	
L.M.	70	-	-	-	-	Volcanic shards	Klett and Erickson (1976)	
Timber Lake Member	50-90; 20-50 at the base; very fine-fine	75-80	10-20	10-20	mainly chert	No volcanic ash; no volcanic rock fragments; moderate sorting; pyrite at the base	<u>This study</u>	Southwest Rim
	70-90	25-30	10-15	35-40	chert	Glauconite	Feldmann (1967; 1972)	Southeast Rim
	80-90; 65 at the base; very fine-fine	50	50	-	-	Pyrite; glauconite; feldspar; volcanic shards	Waage (1968)	

into the normal-bedded subfacies. The basal contact with the Trail City is conformable and occurs at the base of the TLcm. The upper contact with the Colgate Member is planar and erosional, and is usually drawn at the top of the TLfm zone.

The stratigraphic position and texture of the strata, as well as the presence of Ophiomorpha, is similar to the Timber Lake in the type area; however, the strata in the thesis area contain hummocky bedding whereas trough bedding dominates the type strata (fig. 9, 10). The mineralogy of the sediments is different (fig. 51); Waage (1968) reported volcanic rock fragments from the type Timber Lake, but these are not a significant portion of the study area sands.

Colgate Member

The Colgate Member (cross-bedded facies; fig. 38, 52) is composed of light olive gray (5Y 6/1), moderately to poorly sorted, muddy, very fine to medium sand (70-85 percent sand). The member is characterized by cross-bedding and carbonaceous material in the drapes of wavy bedding and in the foreset toes along the lower bounding surfaces of troughs.

The Colgate is typically 7-9 m thick but may be as thin as 2-4 m where major erosion is evident (site 6c, fig. 39). The basal contact of the member is planar and erosional; the upper contact with the Hell Creek is unconformable with variable erosion.

Early workers (Thom and Dobbin 1924; Hares 1928; Dobbin and Reeside 1929) reported Halymenites (=Ophiomorpha) major in the Colgate. Inspection of the strata in the thesis area revealed that, except in rare instances, (sites 4, 6d), Ophiomorpha was restricted to the Timber Lake Member. Ophiomorpha does not occur in the type Colgate at Glendive, a conclusion corroborated by Butler (1980) and Wilde (1983). Early

workers (i.e., Dobbin and Reeside 1929, p. 14-15; Hares 1928, p. 17-18) often included part or all of the Timber Lake strata in the Colgate based on the light color and the lack of an obvious contact in the sand section.

Fluted weathering is a locally prominent characteristic of weathered slopes in the Colgate, but is not confined to that member in the area. The Colgate exhibits fluting to some degree at sites 2, 6, and 7, but is not fluted at site 4. Fluting usually occurs on gentle slopes, not on cutbanks. The upper Timber Lake Member and some sands of the lower Hell Creek also exhibit fluting.

The Colgate of the thesis area is one-third the thickness and is characterized by sedimentary structures and bedding sequences different from those of the type Colgate at Glendive, but both occur at the same stratigraphic horizon (between the Timber Lake Member = hummocky-bedded facies and the Little Beaver Creek Member). The sediment of the type Colgate is better sorted than that in the study area but contains a comparable mineral suite (fig. 51).

Colgate affinities.--The Colgate was originally included in the Lance Formation on the basis of age (the member was thought to be Tertiary); later it was included in the Fox Hills because it was thought on the basis of fauna to be marine. The Colgate has been used as a convenient marker at the base of the lignite-bearing section.

At Glendive, the type Colgate contains sedimentary structures and bedding sequences similar to those of the overlying sands of the Hell Creek Formation (Butler 1980; Wilde 1983). In addition, the Colgate is separated from the underlying Timber Lake by an

erosional surface but is gradational with the overlying Hell Creek (Butler 1980). The stratigraphy of the member is similar along the Musselshell River (Jensen and Varnes 1964). On this basis, some believe that the unit properly belongs in the Hell Creek, at least in these areas.

In the thesis area, the basal contact of the Colgate is planar and erosional, but the upper contact also shows the effects of minor to major reworking. The similarity of bedding and sedimentary structures between the Colgate (with the exception of certain strata at sites 1a, 4, and 7a) and the overlying Hell Creek strata is superficial. The stratigraphy at Fort Peck is similar to that in the thesis area.

Although the Colgate in the region contains diverse strata and exhibits various relationships with the adjacent strata, it should be retained as a member in the Fox Hills mainly to avoid the task of revising an entrenched stratigraphic terminology. However, its use should be tempered with a clear understanding of its variable character.

Member vs. lithofacies.--At present, the Colgate strata in the type area are labeled "member" by the South Dakota Geological Survey but "lithofacies" in a separate body of literature; in North Dakota the situation is similar, the Geological Survey uses "member" (Bluemler et al. 1980; Carlson 1979, 1982) statewide but "lithofacies" is used in other publications (in the Missouri Valley: Erickson 1971, Klett and Erickson 1976; for a statewide area, Cvancara 1976).

Figure 52. The Timber Lake and Colgate Members of the Fox Hills Formation (site 7a). The erosional Timber Lake-Colgate contact (A) occurs atop the locally discontinuous TLfm; the Hell Creek (Little Beaver Creek Member)-Fox Hills contact occurs at (B). Root molds occur below (B) and tiered galleries of O. borneensis persist to the top of the TLfm. The Colgate is 6 m thick.



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The term "lithofacies" has never been formally applied in the study area but the work of Cvancara (1976) makes a review of its application necessary.

On the Cedar Creek anticline, where the member terminology was developed, the Colgate is essentially tabular, but in the type area, where the lithofacies concept was developed, Waage (1961; 1968) showed that Colgate to be: variable in thickness, thickening and thinning at the expense of the Bullhead (first noted by Laird and Mitchell (1942) in the Missouri Valley of North Dakota); laterally discontinuous; of variable distribution, occurring in the lower Hell Creek as well as within or atop the Bullhead; and well developed only in the southwest corner of the type area.

Waage (1968) did not consider the Colgate strata as constituting a viable, regional map unit. In order to retain the stratigraphic identity of the Colgate and Bullhead and thereby detail their environmental significance, Waage (1968) demoted them to "lithofacies" within the Iron Lightning Member.

The definition of the Iron Lightning Member embodies the following implicit assumptions: the Colgate occurs intimately associated with the Bullhead strata (lateral facies of one another); the Colgate is variable in lateral and vertical occurrence; and that the Colgate and Bullhead both occur in the member.

Carlson (1979; 1982; in Bluemle, Anderson, and Carlson 1980) viewed the Colgate as an operational unit, a marker useful for subsurface correlation, and treated the unit as a regionally

continuous, tabular sand with a fixed stratigraphic position. This rationale developed partly from and paralleled those of the early workers on the anticline and in the type area. He further believed that the use of Iron Lightning obscured the fact that the Colgate was the unit most often in contact with the Hell Creek. As a result, Carlson (1979) supported the use of the Colgate as a member, finding it especially useful in subsurface correlation. In 1982, Carlson suggested that the Linton Member (Klett and Erickson 1976) that occupies the "key" position in the Missouri Valley be considered part of the Colgate since it occurs at the same stratigraphic horizon and is grossly similar lithologically; this suggestion was partly intended to halt the proliferation of members in the area.

The Colgate should continue as a member in the western region. The absence of the Bullhead in outcrop along the southwestern rim of the Williston Basin (fig. 53) and the region to the west precludes the use of the term "Iron Lightning" in the thesis area. Lithofacies can be applied informally across formation or member boundaries, but should not stand alone thereby gaining defacto equality with the formal nomenclature. In the subsurface a vertical cutoff can be used to separate the Colgate Member from the Iron Lightning.

In the Missouri Valley, the extent and character of the Colgate is poorly documented (Feldmann 1967, 1972 and Carlson 1982 contain few and widely spaced sections) and the picture is further complicated by the recognition of the Linton Member (Klett and

Erickson 1976). The Linton is clearly regionally extensive but its relationship to the Colgate (i.e., overlying, laterally equivalent) has not been made clear.

Abandoning the term "lithofacies" in the Missouri Valley would lead either to a proliferation of members or to a suppression of detail as distinctive strata are lumped into too few members. The use of "lithofacies" in conjunction with the Iron Lightning Member allows the addition of stratigraphic detail and environmental clarification without resorting to formal terminology, thereby allowing freedom and flexibility in a complex section. Over-emphasis on a "capping sand" detracts from the interrelationships in the upper Fox Hills.

Regional Stratigraphy

Exposed sections

Southwest rim.--The sedimentary structure facies, and corresponding members, as defined for the lower Fox Hills in the study area, are recognizable in outcrops along the southwest rim of the Williston Basin (fig. 53; loc. 1-4; Appendix A, part 1). Over the same area, the Colgate Member is variable in thickness and contains differing sedimentary structure facies. The Bullhead strata do not occur in this area or to the west.

The strata at Fort Peck (loc. 1), previously undifferentiated (fig. 3; Jensen and Varnes 1964), are divided into the following members (from the base; fig. 53, 54): Trail City (11 m), composed of thinly interbedded silt and clay capped by two 0.5-m-thick hummocky beds (HbM) containing Cosmorhappe and O. nodosa; Timber

Figure 53. Stratigraphy of the Fox Hills Formation in outcrop along the south rim of the Williston Basin. The section to the east is thicker and the Bullhead lithofacies is present in the upper Fox Hills; hummocky bedding does not occur in the eastern Timber Lake. The members, as defined in the study area, can be recognized all along the southwest rim of the Basin.

Legend

Trough cross-bedding	(TCB)
Hummocky bedding	(HB)
Massive-hummocky	(MH)
Massive	(M)
Interbedded	(I)

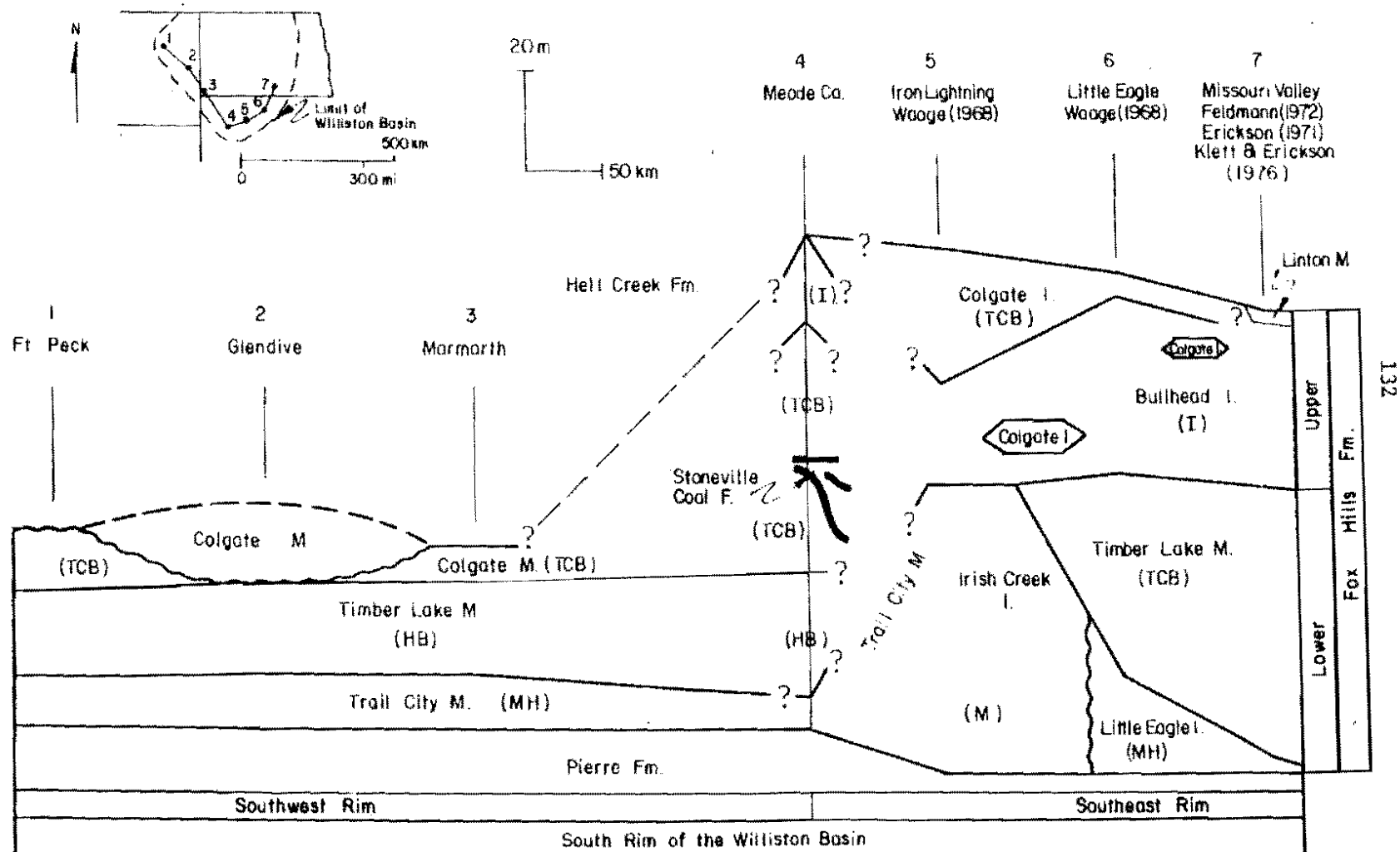


Figure 54. The lower Fox Hills Formation (site 1-1) near Fort Peck, Montana. The Trail City-Timber Lake contact (A) is placed at the change upsection from interbedded silt and clay (and minor sandy silt) to sand; B marks the base of preserved hummocky bedding. The zone between (A) and (B) is wholly bioturbated sand. (C) marks the level of two hummocky beds, analogous to those in the Trail City of the study area (site 1a), containing O. nodosa and Cosmorhaphis. The Timber Lake Member contains M (not W) zones atop hummocky beds; O. nodosa, in addition to locomotion traces, are abundant in this member. Interval (A-B) is 2 m.

Figure 55. The Trail City-Timber Lake contact (site 2-1) near Glendive, Montana. The contact (A) marks the basal hummocky scour of the Timber Lake; the finely interbedded silt, clay and mudstone of the Trail City Member occur below. Four meters of Trail City is exposed.



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Figure 56. Two turbidites in the upper Trail City Member (site 2-6) south of Glendive, Montana. (A) marks the contact between the two. The base of the upper turbidite contains disturbed bedding (?) or rip up clasts (?). Not shown on the photo are an overlying T4 layer (upper interval of parallel lamination), and T5 layer (interval of massive mud). Water escape structures (B) occur in the T4 layer of the lower turbidite. These beds are interpreted as distal turbidites. The tape is 0.33 m.



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Lake (16 m) composed of normal hummocky beds (HbFbXb) containing O. nodosa and capped by M (not W) zones; and Colgate (11 m) composed of medium scale trough cross beds with flat cobble lags (edgewise conglomerates of Jensen and Varnes 1964). The contacts of the Colgate are unconformable and several meters thickness may be missing from the top of the formation (Jensen and Varnes 1964).

The lower Fox Hills section at Glendive (loc. 2) previously designated the Timber Lake Member (fig. 3; Butler 1980), is divided into the Trail City and Timber Lake Members (fig. 53, 55). The Trail City Member (10 m) consists of mixed and thinly interbedded clay and silt and medium bedded mudstones (containing the fodinichnia Rhizocorallium); distal turbidities occur in the upper portion of the member (site 2-5, fig. 56). The Timber Lake Member (20 m) contains normal bedded and overlying amalgamated subfacies; the locomotion trace Gyrochorte occurs in ferruginous mudstone layers near the base (sites 2-3) and tiered galleries of O. borneensis occur in the amalgamated strata at the top (sites 2-1, 2-2). The upper contact of the member is erosional and may be channeled (site 2-2).

The Colgate Member (12-24 m), in the vicinity of its type locale, is retained here as defined by Butler (1980) and Wilde (1983). The member contains a bedding sequence (fig. 11, 12) different from that in the study area or at Fort Peck.

The Fairpoint Member (fig. 3; Pettyjohn 1967) in Meade County (loc. 4) is equivalent to all of the lower and part of the upper Fox

Hills section; only the Timber Lake Member in the lower Fox Hills, however, is defined with confidence. The Trail City Member (7 m) is probably present, corresponding to part of the section described by Searight (1933, p. 6, unit 1 of the Shale and Sandstone Member) and Pettyjohn (1967, p. 1364, unit 3). The Timber Lake Member (24 m) is hummocky bedded and contains O. nodosa (corresponds to units 4-15, Pettyjohn 1967, p. 1364). The lower portion of the upper Fox Hills section contains the lignite-bearing Stoneville Coal facies, a unit having no counterpart in outcrop regionally, and trough cross-bedded sands; the overlying strata, the White Owl Creek Member (Pettyjohn 1967), contains the ~~Bullhead-like~~ Enning facies.

It is important to note that only 50 km to the northeast the Trail City Member comprises the entire lower Fox Hills and that the Iron Lightning Member, containing the Colgate and Bullhead lithofacies, is fully developed. The hummocky bedded Timber Lake Member occurs in roadcuts along U.S. 34, nearly to the border of Ziebach County.

Southeast rim.--In outcrops along the southeast rim of the Basin (fig. 53, loc. 5-7), the lower Fox Hills section is twice the thickness of comparable strata on the southwest rim; the Trail City (Irish Creek lithofacies) comprises the entire section at location 5, but the Timber Lake becomes dominant to the east. The hummocky-bedded Timber Lake sand is absent from the eastern exposures being replaced eastward by mixed sediment in the Trail City and sands of the trough cross-bedded Timber Lake. The ichnofossil suite is reduced to Ophiomorpha and overshadowed by a rich fossil marine fauna.

The upper Fox Hills section (Iron Lightning Member) along the southeast rim of the Basin (fig. 53, loc 5-7) is five times the thickness of the section in the study area and contains the Bullhead strata that are absent in the west. The Colgate and Bullhead comprise equal amounts of the section at location 5 but the Bullhead becomes dominant to the east. The Colgate occurs as lentils within the Bullhead and usually caps the Fox Hills section. At location 4 where Bullhead-like strata (White Owl Creek Member) are first seen (going east) no Colgate-like strata caps the section.

Subsurface sections

Lithologic characteristics form the basis for subsurface correlations; the Fox Hills typically consists of (from the base) 10 m of silt and clay (Trail City) overlain by 27 m of sand (Timber Lake, Colgate). The Trail City Member can be defined on the basis of lithology alone, although little lithologic contrast occurs across the gradational lower contact with the Pierre Formation. Contacts between members in the overlying sand section are best defined on the basis of sedimentary structures and ichnofossils; the lack of lithologic contrast makes difficult the separation of these members in the subsurface.

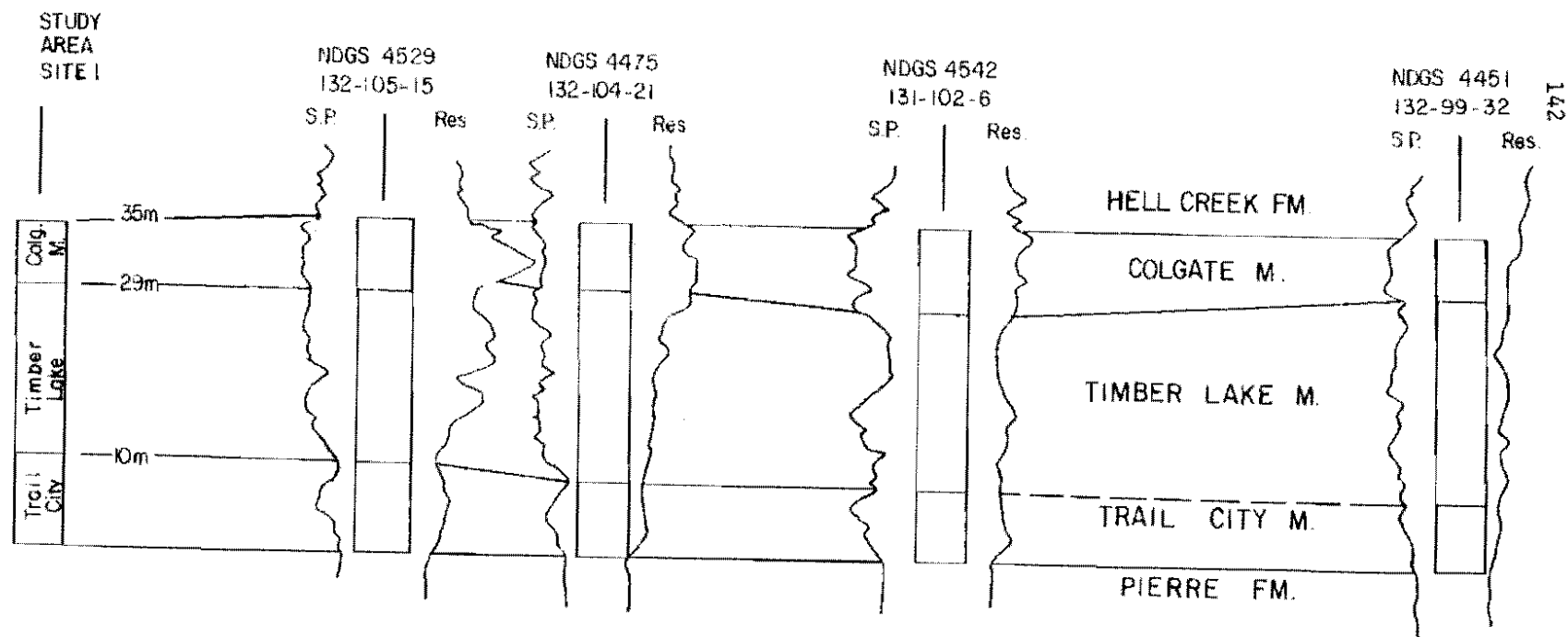
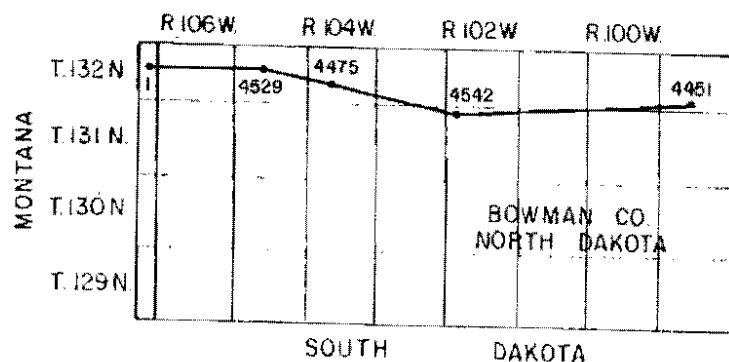
On the basis of experience at outcrop, the Fox Hills-Hell Creek contact, when defined by lithology alone, could be placed, where the base of the Hell Creek is sand (site 3-6), as much as 20 m too high in the section. Mineral composition may be an indicator of member or formation boundaries regionally (fig. 57): the mineral suite in

the Colgate, including that from the study area, Glendive, and the southeast rim exposures, is largely devoid of volcanic rock fragments while the overlying Hell Creek sediments are rich in these fragments; however, in the east, volcanic rock fragments occur in the Timber Lake.

I believe that the character of the Fox Hills, as seen in outcrop in the study area, remains comparable in the subsurface for 10s of kilometers to the east (fig. 57). It would seem unlikely that the formation would reach a thickness of over 100 m just east of the study area as reported by Cvancara (1976, pl. 4, loc. 11); ^{Since} ~~but~~, in a nearby well, NDGS 4542, the thickness of the Fox Hills would appear to be similar to that in the study area (fig. 57). Lignite, similar in stratigraphic position to that in Meade County, South Dakota (Stoneville Coal facies), has been reported from the upper Fox Hills (Cvancara 1976, pl. 2, 4, loc. 12), but it seems unlikely that lignite would occur near the base of the Fox Hills section as reported by Cvancara (1976, pl. 2, 4, loc. 6).

In the light of surface exposures, it seems doubtful that any of the members, especially the Timber Lake (hummocky bedded), maintain their identity, as defined in the study area, easterly beyond the midline of the Williston Basin. In wells in Adams County, 100 km east of the study area, the Fox Hills section is dominated by clay and silt with minor sands (Carlson 1979, # 4700). Carlson recognized the Timber Lake in that area but the section may only contain Iron Lightning and Trail City.

Figure 57. Proposed subsurface correlation of the Fox Hills Formation in Bowman County, North Dakota (modified from Carlson 1979, pl. 2).



DEPOSITIONAL ENVIRONMENTS

Depositional Model

The Fox Hills Formation represents shallow marine deposits, predominately of storm origin, that were laid down on a broad shelf in water depths less than 37 m, marginal and seaward of the prograding Hell Creek delta system. The model is largely based on the storm-origin interpretation of hummocky bedding (Harms et al. 1975; Dott and Bourgeois 1982), and an evaluation of the type and distribution of trace fossils. The following environments are recognized (from the base; fig. 58, 59, 60): basin-slope (Pierre Formation); outer shelf (Trail City Member); inner shelf (Timber Lake Member); shoreface-channel (Colgate Member); and lower delta plain channel-overbank (Little Beaver Creek Member of the Hell Creek Formation).

During Fox Hills time the climate was humid subtropical, the prevailing winds were westerly, and seasonal changes were minimal (Dott and Batten 1971). The rate of the regression of the Fox Hills sea across the study area was high, 400 km per 0.5 million years (Gill and Cobban 1973). The sediments were probably derived from the clastics or metasediments of the Elkhorn Mountains and brought east to the shore by the Hell Creek drainage system (Butler 1980). Once at the shoreline, sediment was deposited: (1) steadily, from suspension fallout, on the outer shelf (massive component-Trail

Figure 58. Depositional environments of the
Fox Hills Formation in the study
area.

Figure 59. Panorama of depositional environments in the Fox Hills Formation of the study area. The arrows indicate the direction and means of sediment transport. The Fox Hills is not considered to be part of the Hell Creek deltaic complex.

LEGEND

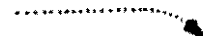
Longshore current



Storm Surge



Suspension Fallout



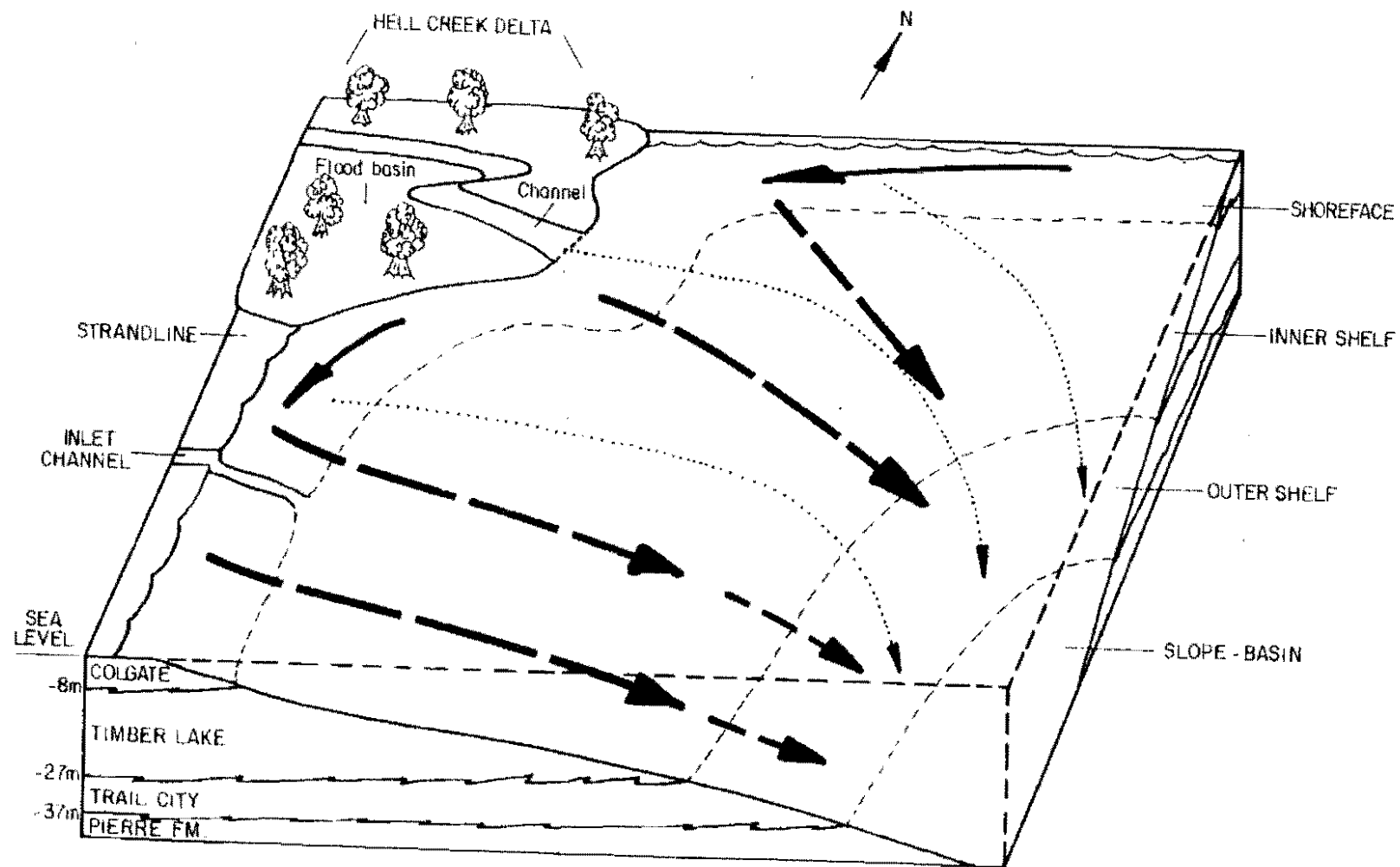
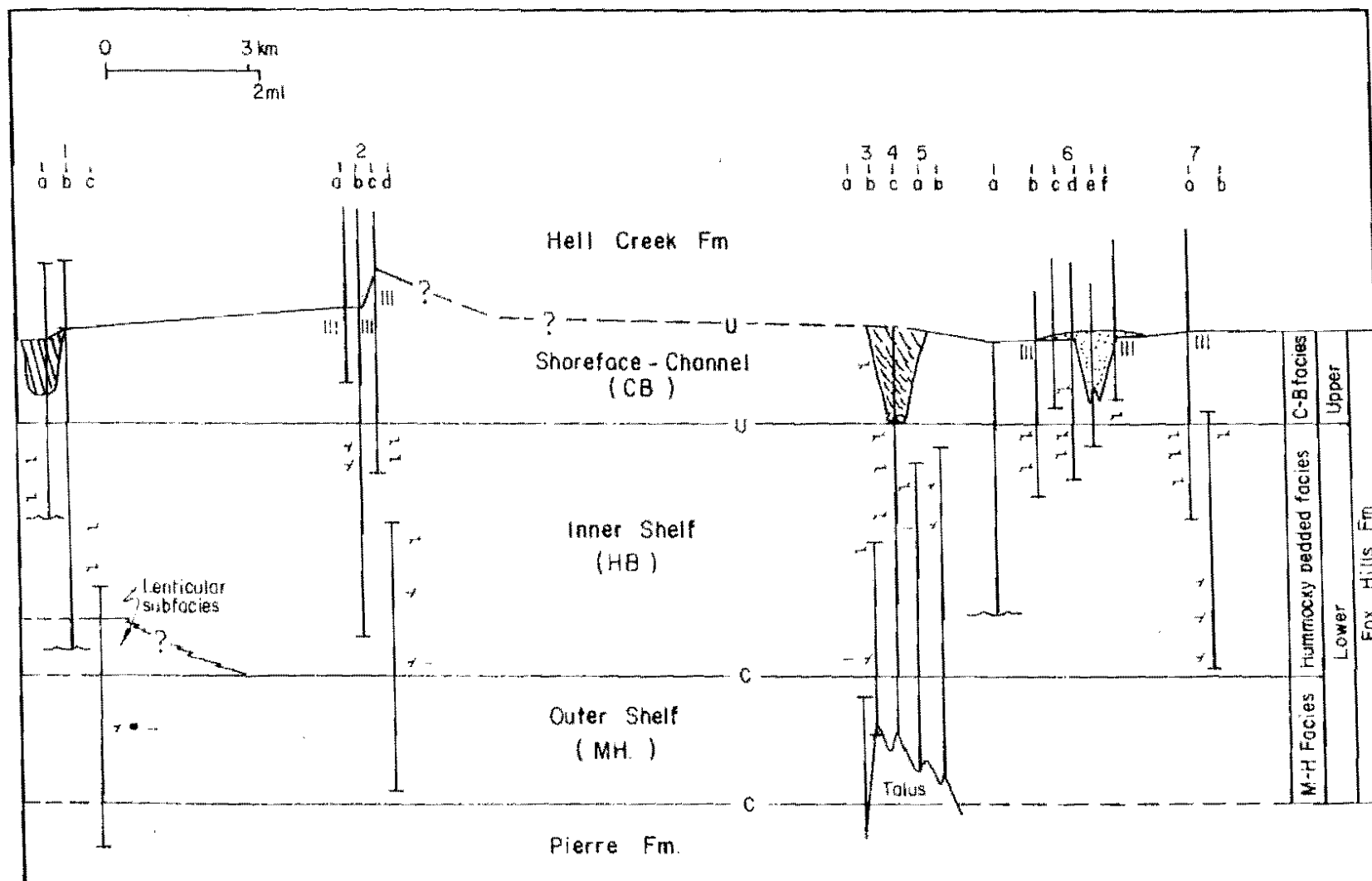


Figure 60. Cross section of the Fox Hills in the study area showing depositional environments. The legend is shown on figure 39.



City Member); (2) episodically, in the wake of storms, on the inner shelf (hummocky component=Trail City Member, hummocky bedded facies=Timber Lake Member); and (3) through current dominated shoreline or tidal (?) channel processes (cross-bedded facies, Colgate Member).

A barrier bar-deltaic model (Trail City=offshore; Timber Lake=barrier bar; Bullhead=delta front, prodelta, or lagoon; Colgate=brackish channels; Linton=brackish channels) has been proposed for the southeast Basin rim (Waage 1968; Feldmann 1967, 1972; Erickson 1971; Klett and Erickson 1976). Storm deposits have been noted in these exposures: Cvanara (1976, p. 11) suggested that sandstone interbeds of the Trail City and lower Timber Lake were of storm origin; Erickson (1971) believed that part of the cross-bedded strata of the upper Timber Lake represented storm deposits.

In the Glendive area, Butler (1980) proposed a wholly deltaic model (lower Fox Hills=delta front; Colgate=lower delta plain channels). In the Rock Springs, Wyoming, area, Land (1972) outlined a barrier bar-estuarine model.

Sedimentary structures

Wavy bedding.--Wavy bedding (fig. 15, 16) is composed of two structures--wave ripples and drapes--that represent a minor variation in a generally low energy regime and, therefore, form a minor but important indicator of low energy conditions in the hummocky-bedded and cross-bedded facies.

Wave ripples are produced by oscillating wave motion under relatively low energy conditions in the absence of currents (Harms

et al. 1975, p. 58).

Drapes represent the compacted bases of originally thicker clay layers (1 cm was the critical thickness for preservation) that were deposited from suspension during slack-water periods (Hawley 1981). The higher energy conditions accompanying the deposition of the overlying sediment (ripples or other bedform) removed the noncompacted portion of the clay material. According to Hawley (1981), drapes are deposited during a single slack-water event, not built up over a period of time from a series of depositional events, as suggested by Terwindt and Breusers (1972).

Wavy layers and bedding require a repetition of low energy, oscillation and slack-water events, of the critical magnitude to allow the deposition and preservation of both ripples and clay drapes. Events such as tides (Hawley 1981) or a series of small scale storms could produce such structures.

Wavy layers are useful in marking the tops (end stages) of higher energy depositional events such as hummocky bedding or cross-bedding. For example, a slack event between periods of active bedform migration could produce a wavy layer atop cross-bedding (fig. 10).

Hummocky bedding.--In the study area, hummocky bedding, known only from shallow marine deposits in the rock record (Dott and Bourgeois 1982; Allen 1982), dominates the lower Fox Hills and contains nearly all the ichnofossils in the formation.

In hummocky stratification (fig. 19): the mantling character of the laminae suggests deposition from suspension; the swale-

hummocky-undulatory character of the laminae suggests a component of oscillation. The deposition of hummocky laminae probably results from suspension fallout from the water column in the presence of major oscillatory components (Harms et al. 1975; Dott and Bourgeois 1982).

Deposition in the L-set is essentially continuous. Sand is deposited in sharply defined undulatory laminae; each lamina reflects a single wave or wave train. Variations in intensity cause undulatory surfaces. The configuration of each succeeding lamina is due in part to the depo-surface morphology and in part to intrinsic properties of the depositional process.

Hummocky beds (HFX) are deposited essentially without interruption during a single event (fig. 20); they are the record of decreasing energy in the wake of a high energy event. Scour at the base attests to high energy conditions; wave ripples, and overlying W or M zones, at the top, attest to low energy conditions.

Although the exact mechanisms related to deposition remain problematic, Dott and Bourgeois (1982) suggested that: (1) during storms, sand at the shoreline is suspended by wave pile-up; (2) retreating storm surges carry sediment seaward and deposit it below fair weather wave bases but above storm wave base under oscillatory conditions; and (3) farther seaward, turbidites or laminites are deposited. With the return of normal conditions, silt and clay settle out forming a drape that results in an M zone or, if touched by periodic oscillatory conditions, a W zone. These overlying layers may rest conformably or atop a scoured or reworked

surface. Discussions of the mechanisms related to hummocky deposition are contained in Dott (1983), Allen (1982), Bourgeois (1980), and Hamblin et al. (1979).

Kresia (1980) and Dott and Bourgeois (1982) both developed systems, based on the internal zone sequence in hummocky beds and on the sequence of hummocky bed types, that show relative energy during emplacement and relative distance from source. Amalgamated bedding indicates proximal or high energy deposits; isolated hummocky beds represent distal or lower energy deposits. When applied to the Fox Hills section, this model suggests increasing energy and increased proximity to source upsection.

Trough cross-bedding.--Trough cross-bedding results from deposition in an upper flow regime, unidirectional, current. Large and medium scale trough cross-bedding are deposited by migrating dunes (Harms and Farnestock 1965). Small scale troughs encased in horizontal lamination comprise a variation of "scour and fill" cross-bedding and represent the results of minor variations in flow velocity that cause scours in the upper plane bed deposits (Reineck and Singh 1975, p. 95).

Epsilon cross-bedding.--Epsilon cross-bedding is formed as a result of point bar development in a meandering channel and was first identified in tidal channels (Allen 1963, p. 104). The channel floor corresponds to the basal planar scour and the heterolithic foresets result from alternating high energy (sand) and slack (mud) periods.

Bioturbation patterns

An ichnofossil represents the preserved indication of an organism that adapted to a certain set of environmental conditions. Once a certain set of conditions is established in an area (e.g., salinity, food supply, and substrate), a characteristic infauna occurs.

Bioturbation is typically confined to the upper 0.3-0.5 m of the substrate. Under the ideal scenario, in which bioturbation keeps pace with steady, continuous deposition, the zone of active bioturbation moves upward with the surface layer producing a wholly mixed, massive, reworked deposit. Under a regime of variable sedimentation rates, communities can be buried and reestablished resulting in alternating bioturbated and nonbioturbated layers (Reineck and Singh 1975; Howard 1978).

Organisms that "mine" the substrate, pascichnia or fodinichnia, have the potential to completely destroy primary inorganic sedimentary structures through reworking; organisms that produce domichnia traces rework the sediment only partially, even under conditions of intense bioturbation.

Massive strata in the Trail City Member indicate thorough bioturbation coupled with slow, steady, rates of deposition. In the hummocky beds of the Trail City and overlying Timber Lake Members, the ichnofossils are confined to zones of bioturbation (fig. 61, 62). These zones attest to burrowing episodes interspersed with periods of rapid, hummocky, sedimentation. Under this regime, the trace fossils do not reflect conditions during the depositional event, as in the

Figure 61. Irregular boxworks of O. nodosa in the normal bedded subfacies (site 2b). O. nosoda occurs as irregular boxworks at the top of hummocky beds. Burrow at (A) is 4 cm.

Figure 62. Zoned bioturbation in the lower Fox Hills (site 5a). An unidentified fodinichnia occurs at (A); O. nodosa occurs at (B). Hummocky lamination is preserved at (C). The strata are interpreted as lower energy environments on the seaward side of the inner shelf. Pocket knife is 7 cm.



Figure 63. Environmental distribution, burrowing habits, and trace fossil analogues for some modern burrowing shrimp. Most of the reports concern investigations of the surf zone.

Ichnofossil analogue		Modern Species	Behavior; Burrow, Environment	Author	
non-nodular lining	nodular lining	<u>Ophiomorpha</u>	<u>C.</u> ¹ <u>major</u>	Filter feeder, communal; shafts lead to tiered galleries 1-5 m below substrate surface; moderate to well sorted sand; intertidal, shallow subtidal, tidal channel bars; marine to brackish water.	Pohl (1946); Weimer and Hoyt (1964); Smith (1966); Frey and Howard (1969); Frey and Mayou (1971); Hertweck (1972); Pryor (1975); Frey et al. (1978).
			<u>C. filholi</u>		Devine (1966).
			<u>C. biformis</u>	Detritus feeder; burrow system less regular than for <u>C. major</u> , 0.5 m deep; muddy sand intertidal, tidal channel bar, shallow shelf; marine to brackish water.	Frey and Howard (1969); Hertweck (1972); Smith (1966).
	Thalassinoides	<u>C. islagrande</u>	Well sorted sand; shallow shoreface bars. Muddy sand; intertidal, shallow subtidal, tidal channels.	Hill and Hunter (1972). Smith (1966); Frey and Howard (1969).	
		<u>C. californiensis</u>	Detritus feeders; burrows 0.5 m deep; muddy sand; lagoons.	MacGinitie and MacGinitie (1949); Thompson (1972); Homziak (1981).	
		<u>U.</u> ² <u>pugettensis</u>		MacGinitie and MacGinitie (1949); Thompson (1972).	
	?	<u>Callianassa</u> sp.	Habit and burrow morphology unknown; outer shelf (collected at depths of 500-600 m).	Kern and Warme (1974).	

¹C. = Callianassa ²U. = Upogebia

¹C. = Callianassa

²U. = Upogebia

massive strata, but are a record of interevent conditions.

Typically, no bioturbation occurs in the wavy layers (W zones) in the Timber Lake Member. The M zones observed at Fort Peck, however, were thoroughly bioturbated and are interpreted as fair weather deposits. The lack of bioturbation in W zones may stem from improper substrate, or nonpreservation of bioturbated layers.

Ophiomorpha.--Ophiomorpha nodosa (forms A, B, and C) is found in the hummocky beds of the Trail City and lower Timber Lake Members; Ophiomorpha borneensis occurs alone in the upper half of the Timber Lake. The morphology of the burrows and the association of the burrow types is dependent on the species (maturity and feeding habit) of the burrowing organism, the character of the substrate (as a function of the distance from shore, sediment type and source, and the mechanism and rate of deposition), and the environmental conditions during burrowing. The amount of the community preserved is dependent on the amount of erosion prior to the deposition of the overlying layer (usually a hummocky bed).

In the modern setting, callianissid shrimp and their close relatives of the genus Upogebia, as well as other thalassinids, construct burrows similar in form to Ophiomorpha. From observations of these modern analogues the following trends have been noted (fig. 63; Frey and Howard 1969; Smith 1967; Homziak 1981; Frey et al. 1978; Pryor 1975): (1) the character of the substrate is a major control over the type of burrowing species and hence morphology of the burrow system; (2) large species (usually filter feeders;

C. major) burrow in clean sand and high energy environments constructing deep, large diameter burrows with a regular morphology; (3) smaller species (usually detritus feeders; C. biformis, C. atlanticus) burrow in more poorly sorted sand, constructing shallow, irregular, small diameter burrows; (4) the species occur in zones with the smaller forms seaward, but large and small organisms of diverse species often occur in the same general environment as a reflection of minor differences in substrate character and energy conditions; and (5) juveniles form a large part of the shelf plankton and begin burrowing after a couple of molts when they are a few millimeters in diameter. The burrow size increases as the animal matures; the animal does not voluntarily leave the burrow.

The size, diameter, and morphology of Ophiomorpha is due in part to the maturity of the burrowing animal. In the case of an episodic deposit (turbidite, hummocky) the community would be initiated in a sandy, virgin, substrate probably by juveniles. A mature community would contain various sizes and depths of burrows reflecting the age of the burrowing animal and the degree of burrow development. Both occupied and abandoned burrows would be present.

The deep shafts of O. borneensis penetrate several layers of hummocky deposition but O. nodosa forms shallow boxworks within a single hummocky bed. Major erosion (greater than 0.5 meter) would remove any trace of O. nodosa but would leave the deep galleries of O. borneensis largely intact.

The segregated occurrence of the two species of Ophiomorpha is related to substrate and other environmental conditions. The remains of the forms of O. nodosa is a testimony to the low energy of subsequent events; the presence of the form attests to a silty, fine grained sand substrate suitable for detritus feeding. The remains of O. borneensis attests to high energy scour conditions; its presence attests to coarser grained substrates and conditions suitable for filter feeding.

Bathymetry

Ichnofossils.--Ichnofossils have been widely used as paleoenvironmental, especially paleobathymetric, indicators. Ichnofossils are well suited to the task since (Sielacher 1967): (1) the form of the fossil is determined more by behavior than by anatomy--the activity of the organism reflects the environmental conditions in the characteristic trace morphologies; (2) unlike taxonomic groups of body fossils, they are not restricted in time; (3) and traces are essentially non-transportable. Individual ichnotaxa, however, cannot be relied upon as bathymetric indicators without supporting evidence (Osgood and Szmuc 1972; Kern and Warne 1974).

Most paleobathymetric interpretations have been based on the standardized ichnofossil assemblages and concomitant bathyal zonation (distance from shore) distilled by Sielacher (1967; fig. 64) from examples in the rock record. The changes in burrowing habit, and the change from suspension to detritus feeding, that occur

Figure 64. The bathymetric zonation of Seilacher (1967) as applied to the Fox Hills Formation in the study area (modified from Seilacher 1967). O. borneensis occurs in higher energy environments and coarser sand on the shoreward side of the Cruziana facies; O. nodosa occurs in the finer sand and lower energy on the seaward side. The Skolithos, Glossifungites, and Zoophycos facies were not recognized in the study area.

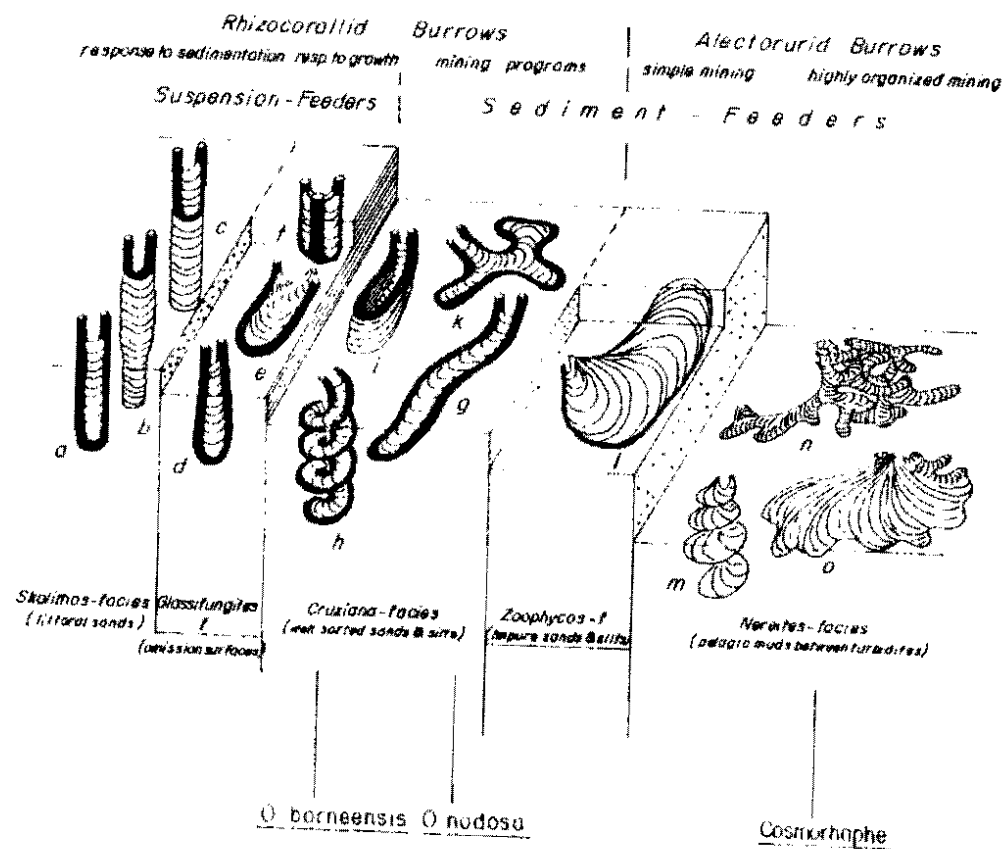


Figure 65. Summary by paleoenvironment, of the occurrence
of Ophiomorpha in the rock record.

Environment	Diameter (cm)	Ophiomorpha		Texture; sedimentary structure	Author
		Orientation	Abundance		
estuary	1.5-4	horizontal	common common	sand, well sorted; trough beds sand, moderately sorted	Land (1972) Klett and Erickson (1976)
restricted bay	3	-	-	sand, well sorted	Davis (1966)
intertidal-foreshore	2 1-3	vertical vertical horizontal	- common common	sand, well sorted sand, well sorted sand, well sorted	Land (1972) Weimer and Hoyt (1964) Pickett et al. (1971)
upper shoreface	large 2	- vertical	- common	sand, well sorted sand, well sorted	Howard (1972) Land (1972)
lower shoreface	1-1.5 large	- horizontal	rare common	sand, poorly sorted sand, poorly sorted; hummocky(?)	Land (1972) Howard (1972)
inner shelf	1-2 1,0.15	- horizontal	- -	silty sand; amalgamated hummocky	Bourgeois (1980)
mid-shelf (80 m)	2.5	horizontal	common	sand, poorly sorted; hummocky(?) sand; laminated grain flow	Land (1972) Neef (1978)
offshore transition	-	-	-	sand; thin hummocky (?) beds	Howard (1972)
outer shelf	small	-	common	sandy silt	Bourgeois (1980)
bathyal (100s m)	3.5-0.3	horizontal vertical		muddy sand; turbidite	Kern and Warme (1974)

seaward are the result of food availability at different depths. However, suspension feeders are largely confined to firm mud or sandy bottoms; sediment feeders are common on soft mud substrates. Loose mud or fecal material (including that produced by detritus feeders) clogs the filtering mechanisms of suspension feeders and prevents colonization by their larvae. As a result filter feeders are unable to inhabit all areas where food is available, notably those controlled by detritus feeders. Clean, sand substrates discourage colonization by detritus-eating forms and may be inhabited by filter feeders as long as food is available.

The bathymetry of the formation is bracketed by Cosmorhappe in the Trail City Member and root molds at the top of the Colgate Member. Cosmorhappe, a member of the Nereites facies, is an indicator of offshore, pelagic conditions and is usually found in muds between deep water turbidities (Hantzschel 1975). The root molds indicate shallow littoral or subaerial conditions.

Ophiomorpha nodosa (forms A, B) occurs with Cosmorhappe in the Trail City Member and alone in the lower part of the Timber Lake Member; the upper Timber Lake Member and the lower Colgate Member contains Ophiomorpha borneensis. Both Ophiomorpha nodosa and Ophiomorpha borneensis represent the Cruziana facies, but O. borneensis inhabits coarser sand substrates (fig. 64).

In modern settings, callianassid shrimp, both filter feeders and detritus feeders, inhabit a variety of brackish and marine environments (fig. 63). In the 1960s Ophiomorpha were erroneously thought to be largely confined to shallow nearshore environments,

and as a result were viewed as shoreline indicators in the rock record.

In the rock record, Ophiomorpha has been reported from a variety of depths and environments (fig. 65). Kern and Warme (1974) reported the presence of Ophiomorpha in offshore turbidite deposits at a paleodepth of a few hundred meters; they suggested that the presence of a sand substrate was the pivotal factor in the establishment of the community. Hummocky deposition represents an analogous situation; hummocky deposits are episodic, and sand is delivered to offshore areas that would not ordinarily have sand bottoms. The overprinting of the normal seaward substrate zonation by hummocky sand beds greatly reduces the bathymetric significance of Ophiomorpha.

Sedimentary sequence.--Given that subsidence and compaction are minimal, the preserved thickness of a shoreline, barrier island or delta sequence can be used to estimate the original water depth (Klein 1974). The process was applied with the assumptions that the Fox Hills in the thesis area represents a shoreline or barrier sequence, and that deposition was essentially continuous with only minor unconformities. The Pierre-Fox Hills contact is the base of the sequence; the Colgate-Hell Creek contact is taken as sea level. The water depth equals 37 m. Normal wave base would be at a depth of 7-9 m, storm wave base at a depth 25-27 m. These depths compare well with those given for modern and ancient examples (Klein 1974), but may be shallow for the outer shelf (Harms et al., 1982, p. 8-14). Depth estimates are similar for other exposures

along the southwest rim of the Basin; however, in the type area wave base exceeded 43 m and the total depth of the water for the Fox Hills exceeded 73 m (Cvancara 1976).

Environmental Interpretation of Sedimentary Structure Facies

The section represents a shoreward (upsection), shallow marine sequence as evidenced by (fig. 58, 60): (1) a stratigraphic position between the underlying marine Pierre Formation and the overlying continental Hell Creek; (2) an upward increase in sorting and grain size from poorly sorted, sandy silt to moderately sorted, fine sand; (3) an upward change in trace fossils (all contained in hummocky bedding) from pasichnia (Nerietes facies) to domichnia (Cruziana and Skolithos (?) facies); (4) an upward change in sedimentary structures from suspension dominated, through oscillation dominated, to current dominated; and (5) and in the hummocky-bedded facies, an upward change from isolated hummocky laminites, through normal-bedded, to amalgamated.

In the lower Fox Hills, the upsection increase in median grain size and the difference in texture between the Trail City and Timber Lake are related to depositional mechanism and distance from shore. The poorest sorting and finest grain sizes occur in the suspension-fallout deposits (massive component, Trail City); the hummocky beds show a regular increase in median grain size upward (from distal to proximal), but are all moderately sorted with little lateral variation in sorting along a single bed.

The coarsest grain sizes occur in the current dominated deposits where sorting is moderate to poor and lateral variability, reflecting fluctuations in the current, is relatively high.

Massive-hummocky facies

The massive-hummocky facies of the Trail City Member is interpreted as having been deposited in the outer shelf environment below fair weather and storm wave base (fig. 58). This interpretation is based on: (1) the fine grain size of the deposit, mostly silt and clay; (2) the lack of current or oscillatory structures (with the exception of hummocky bedding); (3) the stratigraphic position between the Pierre Formation (marine basin deposits) and the Timber Lake Member; (4) the occurrence of similar deposits in the rock record that have been interpreted as subshoreface (Land 1972; Masters 1967; Harms et al. 1975); (5) recognition of similar deposits in modern shelf environments (Reineck and Singh 1971; Gadow and Reineck 1969; Reineck and Singh 1975; Howard and Reineck 1981); and (6) the presence of Cosmorhaphe, an ichnofossil of the Nereites facies.

The massive and hummocky components of the facies are the result of differing mechanisms and rates of sedimentation. The massive component of the facies is a result of slow, steady rates of sedimentation; bioturbation kept pace with deposition producing a largely reworked deposit. Remnant silt and clay interbeds exhibit diffuse, gradational contacts, a result of a gradual change in sediment type. Deposition of each of the hummocky beds was the result of a single, high energy, storm event as witnessed by the

overall coarser grain size, the preserved lamination in the lower portion of the beds, and the bioturbation of the upper portion of the beds. The coarser sediment of the hummocky beds was brought in from shore.

Only the deposition of suspended sediment is significant on the outer shelf (Drake et al. 1972; Smith and Hopkins 1972). Kulm et al. (1975) identified three layers at which significant transport to the outer shelf, largely passive, occurs: (1) the surface turbid layer (at the seasonal thermocline) that carries sediment seaward during times of major wave activity or peak river discharge; (2) the mid-water layer (the most stable zone, coinciding with the permanent thermocline and the pycnocline) that moves sediment shelfward from the overlying water column and the surf zone; and (3) the bottom turbid layer that transports sediment from the overlying water column, surf zone and the bottom itself. The bottom turbid layer is most pronounced over muddy areas and can form a low density bottom current on the outer shelf.

The massive component is the product of deposition from the transport zones delineated by Kulm et al. (1975); hummocky deposition is the result of storm-induced sand redistribution.

The association of Cosmorhappe (Nereites facies), a deep water indicator and Ophiomorpha nodosa (forms A, B, and C; Cruziana facies) in hummocky laminites is a result of a suitable sandy substrate at depth. The occurrence of Ophiomorpha literally moved seaward with the presence of the storm-origin sand deposits.

Hummocky bedded facies

The hummocky facies of the Timber Lake Member of the Fox Hills Formation is interpreted as having been deposited in the inner shelf environment below normal fair weather wave base but above storm wave base (fig. 53). Hummocky bedding represents deposits from episodic storm events; wavy layers represent deposits resulting from a slight variation in energy under tidal influence or from lesser storm events. This interpretation is based on: (1) recognized stratigraphic occurrence between shoreface and offshore (shelf) facies in ancient examples (Harms et al. 1975; Bourgeois 1980; Allen 1982; Dott and Bourgeois 1982); (2) tentative correlation with modern vibrocore and boxcore samples of "low-angle, parallel-laminated sands" (Reineck and Singh 1972; Clifton et al. 1971; Bourgeois 1980); and (3) a lack of current-formed structures such as those that dominate the shoreface environment. Hummocky bedding is known to be marine; hummocky bedding deposited above normal wave base would either be destroyed and replaced by current bedding or be partly preserved and interbedded with typical shoreface deposits.

Lenticular subfacies.--The lenticular surfaces of the Timber Lake Member is interpreted as having been deposited on the outer portion of the inner shelf on the basis of stratigraphic position and sedimentary structures.

The dominance of wavy layers indicates deposition through a repetition of events (monthly tides (?) that were punctuated by hummocky events (distal hummocky deposition). The process forming

the hummocky L-set lentils was erosional; shallow depressions were scooped out of the wavy deposits which were subsequently filled with a single L-set. Ripples at the base of the L-set attest to a time interval between the scouring of the wavy layers and the deposition of the L-set (fig. 25). The basal ripples and those that formed the X zone were continuous with adjacent ripple layers in the wavy bedding. The ripples at the base of the scour preclude the possibility of turbidite deposition that would probably have been instantaneous, creating its own scour, and destroying any existing bedforms. The sand may have collected in scour depressions that acted as energy sinks. After deposition the hummocks may have served as a source of sand for ripples; ripples associated with hummocky horizons are thicker and better developed.

Normal-bedded subfacies.--The normal-bedded subfacies of the Timber Lake Member was deposited shoreward of the lenticular subfacies and is gradational with it.

The hummocky beds contain complete sequences (HFXW). Those at the base of the subfacies are capped by a single drape and show little evidence of scouring; those in the upper half are capped by well developed wavy layers and exhibit W cut-outs. The complete character of the beds indicates optimum conditions for the deposition and preservation of hummocky beds. Energy associated with deposition increased shoreward.

No sole marks were observed at the base of the hummocky beds indicating that deposition was not a result of turbidity currents. Basal scouring did occur, however, as evidenced by W cut-outs and

grain size contrasts across scour surfaces. W cut-outs are not abundant in this subfacies; deposition for the most part is constructive with the hummocky sets laid down atop a clean wavy "pavement".

Bioturbation by Ophiomorpha nodosa is common in the basal portion of the subfacies but rare in the upper half. This contrast may indicate marginal detrital feeding conditions resulting from the coarsening of the sediment.

Amalgamated subfacies.--The amalgamated subfacies of the Timber Lake Member marks the farthest shoreward extent of hummocky bedding; here the depositional process was more destructive than seaward with only the L-sets being consistently preserved.

The presence of Ophiomorpha borneensis indicates both suitable substrate and food availability for filter feeding during inter-hummocky-event intervals. The size and development of the galleries indicates a reasonable time of stability, perhaps lasting through several hummocky events. Intense bioturbation of O. borneensis just below the TLfm at sites 4 and 6 indicates a longer time of stability than at sites 5 or 7.

Cross-bedded facies

The cross-bedded facies of the Colgate Member is interpreted as having been deposited on the shoreface, but also contains a channel subenvironment (fig. 58,59). "Shoreface" refers to the zone between sea level and fair weather wave base. The shoreface strata are best

exposed at sites 2, 6, and 7a; the channel subenvironment occurs at sites 1a, 4, and 7a.

The shoreface strata are characterized by large to medium scale cross-bedding overlain by medium scale tabular cross-beds; several 0.3-0.5 m tabular scour and fill layers usually cap the section (fig. 30; see Cross-bedded facies). Flow directions in the trough bedding are locally consistent, generally westward. The abundance of wavy layers in the section indicates intermittent deposition; the sedimentary structures indicate general upper flow regime depositional conditions.

These strata are interpreted as shoreface on the basis of: (1) the occurrence of upper flow regime bedforms either trough cosets or troughs with horizontal lamination (upper plane bed) in scour and fill bedding; (2) the stratigraphic occurrence between the hummocky-bedded facies and delta plain deposits as recognized in other examples from the rock record (Harms et al. 1975; Masters 1967; Bourgeois 1980; Dott and Bourgeois 1982); (3) the occurrence of a similar sedimentary structure sequence in modern settings (Reineck and Singh 1975; Howard and Reineck 1981; Clifton et al. 1971; Davidson-Arnott and Greenwood 1976); and (4) the presence of a zone of root molds at the top of the unit indicating shallow littoral or subaerial conditions. The deposit is brackish to shallow marine as shown by the presence of Ophiomorpha borneensis in the shoreface deposits at Horse Creek (site 6). The lack of faunal remains, with the exception of rare Ophiomorpha, could be the result of high energy conditions (Howard and Reineck 1981).

The channel subenvironment at site 4 is characterized by an erosional basal contact, a basal lag, upward-fining texture, and trough bedding (fig. 30, 31, 60). Rounded cobbles of the locally absent HCm occur in the lag. The epsilon bedding at site 1a (fig. 60, 71) is interpreted as a channel point bar. Only at site 4 does the channel subenvironment comprise the entire Colgate, elsewhere the channels occur in the upper half of the member (fig. 60).

The channel at site 4 was deposited in marine-brackish conditions based on the occurrence, although rare, of O. borneensis. Migrating tidal inlets in barrier bars or at the shoreline are known to produce channels several meters deep that exhibit lags, trough bedding, and point bar development (Hoyt and Henry 1965; Reddering 1983). Such an origin would fit the evidence at outcrop; the channels occur cut into shoreface deposits and show no connection with the overlying deltaic Hell Creek. The environments were probably analogous to those described by Land (1972) in the upper Fox Hills at Rock Springs, Wyoming.

Regional Environments

Lower Fox Hills

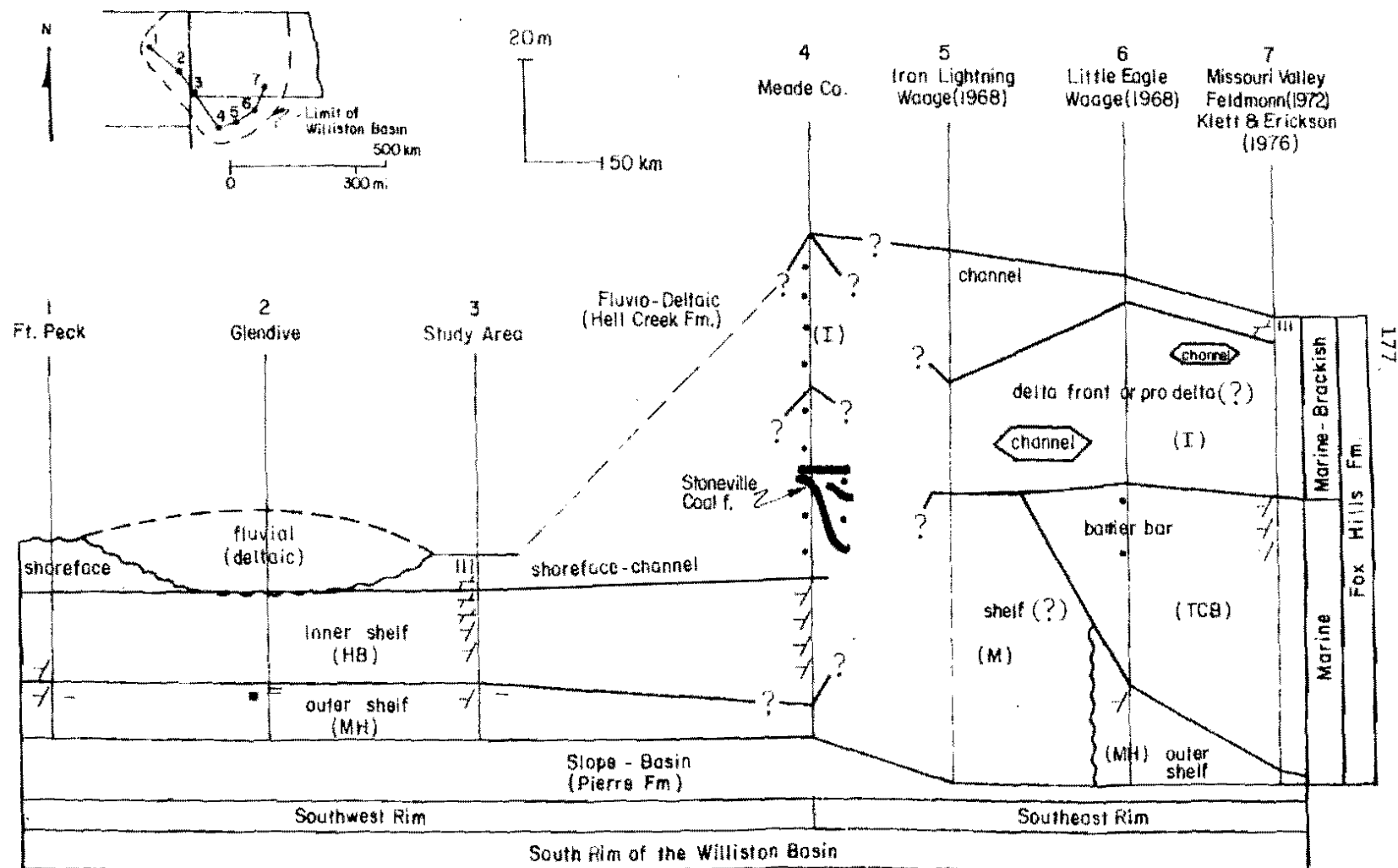
In outcrops along the southwest rim of the Basin (fig. 66, loc. 1-4), the lower Fox Hills represents sediments laid down on a shallow shelf at depths less than 40 m, that are dominated by storm deposits. Deposition occurred during a period of rapid progradation (Gill and Cobban 1973) probably against a backdrop of

Figure 66. Depositional environments of the Fox Hills Formation in outcrop along the south rim of the Williston Basin.

Legend

Trough cross-bedding	(TCB)
Hummocky bedding	(HB)
Massive-hummocky	(MH)
Massive	(M)
Interbedded	(I)

<u>Ophiomorpha</u>	●
(species uncertain)	—
<u>O. borneensis</u>	—
<u>O. nodosa</u>	—
<u>Cosmorhaphis</u>	■
<u>Fodinichnia</u>	—
Root zones	



broad regional uplift and local tectonic quiescence (Gill and Cobban 1973; Clement 1983).

In the lower Fox Hills, the stratigraphic succession, sedimentary structure facies, and trace fossil assemblages on the southeast rim (fig. 66, loc. 5-7) are very different from those to the west. Hummocky bedded storm deposits occur only as a minor component of the Little Eagle lithofacies of the Trail City Member (loc. 6). The column is dominated by the outer (?) shelf (prodelta ?) sediment of the Trail City and the trough cross-bedded, barrier (offshore ?) bar sands of the Timber Lake (Waage 1968; Erickson 1971). The thickness of the section, nearly twice the thickness of that on the southwest rim, and the fossil marine fauna, point to conditions of deep water coupled with subsidence. In the eastern portion of the type area and the Missouri Valley of North Dakota, deposition was largely controlled by northeasterly currents associated with the growth of the Timber Lake sand body (Waage 1968).

Upper Fox Hills

The upper Fox Hills strata, in outcrops along the southwest rim of the Basin (fig. 66, loc. 1-3), are transitional from marine to continental and represent shoreface, shoreface-channel, and fluviodeltaic environments. Butler (1980) ascribed a deltaic fluvial origin to the Colgate in the Glendive area but the fluvial bedding sequences that are diagnostic of the type Colgate do not occur in

the member at Fort Peck, Baker (Wilde 1983), or in the study area.

In the thesis area, environments between shelf and deltaic are present; these strata are partially removed by fluvial (Hell Creek) erosion or overlain, with minor relief, by overbank deposits. In the Glendive area, marine shelf deposits (Timber Lake=hummocky bedded facies=inner shelf) occur in juxtaposition with fluviodeltaic sediments (Colgate=highly meandering lower delta plain facies of Butler 1980) and the erosional contact between the two is locally channeled.

I believe that the Timber Lake-Colgate contact in the Glendive area marks an unconformity characterized by the absence of shoreface deposits (fig. 66). Relief, sometimes major, at the top of the Fox Hills at Fort Peck (Jensen and Varnes 1964) and locally in the thesis area, may represent a continuation of this surface (fig. 66). Possible explanations for this erosion include: local uplift, regional uplift or sea level drop, and contemporaneous reworking of marginal deposits.

Extensive surface mapping and geophysical work has shown that no major uplift occurred on the Cedar Creek anticline prior to the Oligocene (Clement 1983). This and the possible widespread character of the surface rule out major influence from the anticline. Further, the Fox Hills regression passed quickly through the area and the continuity of deposition in the lower Fox Hills and the overall thinness of the formation suggests shallow conditions coupled with regional uplift.

It seems likely that lateral shifts in the Hell Creek (Colgate as well at Glendive) fluvial systems, against a backdrop of broad regional uplift associated with the dynamics of the regression, could have been responsible for the removal, to varying degrees over the region, of the relatively thin shoreface deposits.

The upper Fox Hills at location 4, however, contains environments more closely related to those on the southeast rim; the basal, continental Stoneville Coal facies is overlain by marine (prodelta ?) strata resembling the Bullhead (Enning facies of the White Owl Member of Pettyjohn 1967) indicating a period of subsidence or sea level rise.

In outcrops along the southeast rim of the Basin (fig. 66, loc. 5-7), the upper Fox Hills strata (Iron Lightning Member) are transitional from marine to continental and represent delta front or prodelta deposits (Bullhead) and channel deposits (Colgate). However, the presence of Ophiomorpha throughout the section indicates that marine to brackish conditions persisted to the beginning of Hell Creek deposition. Waage (1968, p. 155-8) reported that, at two horizons in the Iron Lightning, Colgate lenses containing a brackish fauna were overlain by Bullhead strata containing a marine fauna. He concluded that the deposition of the Iron Lightning was punctuated by at least two periods of subsidence or sea level rise. On the southeast Basin rim, the thickness of the section and the faunal evidence points to deposition under low rates of progradation punctuated by periods of subsidence or sea level rise.

CONCLUSIONS

The following conclusions concerning the Fox Hills Formation in the study area in southwesternmost North Dakota are based on: the description, with emphasis on sedimentary structures and the type and distribution of biota, of 23 measured sections from seven major outcrop areas; the textural analysis of 74 sand samples; and the mineralogical analysis of fifteen grain mounts, five from each of the collected outcrops. Conclusions concerning the regional character of the formation are based on the results of in-depth reconnaissance at the major outcrop areas of the Fox Hills along the south rim of the Williston Basin.

1) In the study area, the Fox Hills Formation is a tabular, upward coarsening unit, typically 37 m thick, that consists of a basal silt-clay unit included here as a part of the formation for the first time, and an overlying unit consisting of muddy, subarkosic to sublithic, very fine to medium sand that represents the formation as it had previously been defined.

2) The Fox Hills Formation contains three important sedimentary structures--wavy bedding, hummocky bedding (not previously reported), and cross-bedding. The formation can also be divided into the lower Fox Hills, the basal 29 m dominated by hummocky bedding, and the upper Fox Hills, the overlying portion dominated by cross-bedding.

3) The hummocky bedding of the lower Fox Hills contains plentiful remains of a limited trace fossil suite, including dwelling traces—a single example of Thalassinoides (?) and abundant remains of two species of Ophiomorpha, O. nodosa and O. borneensis, the grazing trace Cosmorhaphe, and unidentified feeding traces. The upper Fox Hills contains rare Ophiomorpha at the base; root molds, leaves (Dryophyllum (?), and horsetail (?) stems (Equisetum (?)) at the top.

4) The conformable Pierre-Fox Hills contact, in contrast to previous practice, is placed 10 m lower in the section at the horizon above which: clay changes upsection to silt and clay; mixed or interbedded strata occur; and ichnofossils become plentiful. The Fox Hills-Hell Creek contact is unconformable, erosional relief is variable, and is placed at the base of the lowest substantial carbonaceous bed in accordance with past practice. Three members--ascending, Trail City, Timber Lake, and Colgate--are recognized in the study area; the Trail City corresponds to the newly added strata at the base of the formation.

5) The Trail City Member (10 m) is a tabular unit composed mainly of mixed, massive, or finely interbedded, light gray (N 7) silt and dark gray (N 5) clay; tabular, 0.5-m-thick, isolated, sandy silt hummocky beds containing Cosmorhaphe, O. nodosa, and unidentified feeding traces occur in the upper half. The rich marine fossil fauna and concretion zones present in the type area do not occur in the west.

6) The Timber Lake Member (19-22 m) consists of hummocky bedded, light olive gray (5Y 6/1), often weathered to moderate brown (5Y 4/4), muddy, very fine-fine sand; O. nodosa occurs in the lower half and O. borneensis occurs in the welded hummocky beds of the upper half. Texturally, the median grain size increases up-section from 4 ϕ to 2.8 ϕ ; the sediment is moderately sorted; and lateral textural variability is relatively low. In the type area the Timber Lake is characterized by trough cross-bedding.

7) The Colgate Member (7-9 m) is composed of light olive gray (5Y 6/1), muddy, fine to medium sand arranged in trough cross-bedding, scour and fill bedding, or epsilon cross-bedding; carbonaceous material is concentrated along the lower bounding surfaces of cross-bed sets and floral remains occur at the top of the unit. The unit is composed of 70-85 percent fine to medium sand; the median grain size is 3.2 ϕ to 2.3 ϕ ; the sediment is moderately to poorly sorted; and the lateral textural variability is relatively high. Clay matrix, mainly illite, probably resulted from feldspar decomposition. The Colgate strata are not associated with the Bullhead strata as in the type area. The regional absence of the Bullhead strata precludes the use of "Iron Lightning" or "lithofacies" in relation to the upper Fox Hills of the study area.

8) The three members in the study area correspond to the three sedimentary structure facies as follows (from the base): Trail City Member (massive-hummocky facies); Timber Lake Member

(hummocky bedded facies); and Colgate Member (cross-bedded facies). The lower Fox Hills corresponds to the Trail City and Timber Lake Members; the upper Fox Hills, separated from the underlying strata by an unconformity, corresponds to the Colgate Member. The members (and sedimentary structure facies), as defined for the lower Fox Hills in the study area, can be recognized in outcrop all along the southwest rim of the Williston Basin; the Colgate Member contains various sedimentary structure facies over the region.

9) In a model based on the storm-origin interpretation of hummocky bedding and the type and distribution of trace fossils, the Fox Hills Formation represents shallow marine deposits, predominately of storm origin, that were laid down in depths of 37 m and less, on a broad shelf, marginal and seaward of the advancing Hell Creek delta system. Deposition occurred: (1) steadily, from suspension fallout on the outer shelf (Trail City Member); (2) episodically, in the wake of storms on the inner shelf (Trail City Member; Timber Lake Member); and (3) continually by current-dominated shoreline or tidal (?) channel processes (Colgate Member). The environments, as defined in the study area, are generally recognizable along the southwest rim of the Basin, but in contrast to the depositional conditions that existed to the east in the type area (i.e., deeper water and subsidence or sea level rise), deposition on the southwest rim was characterized by rapid progradation over a shallow shelf under broad regional uplift and local tectonic quiescence.

APPENDICES

APPENDIX A
FOX HILLS OUTCROPS, SOUTH RIM
OF THE WILLISTON BASIN

APPENDIX A

Part 1

REGIONAL RECONNAISSANCE
SITES

LOCATION 1

Fort Peck, Montana

Site 1-1

Fig. 54

Location.--SW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 4, T. 26 N., R. 42 E; Nashua quadrangle;
slumpblock scarp on the northeast slope of Milk River Hill.

Remarks.--Pierre Formation through the base of the Hell Creek
Formation exposed; excellent exposures of the Trail City
(contains hummocky laminites with Cosmorhapha) and Timber Lake
(hummocky facies; contains Ophiomorpha nodosa).

Previous work.--Jensen and Varnes (1964, p. F15, pls. 1, 2).

LOCATION 2

Glendive, Montana

Site 2-1

Fig. 55

Location.--S $\frac{1}{4}$, Sec. 31, T. 15 N., R. 56 E.

Remarks.--Timber Lake (amalgamated subfacies; O. borneensis layered
galleries; channeled Timber Lake-Colgate contact) Member-
Hell Creek Formation.

Previous work.--Wilde (1983).

Site 2-2

Fig. 82

Location.--NE $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 36, T. 15 N., R. 35 E.

Remarks.--Exposures of the Trail City, Timber Lake (hummocky bedded facies; amalgamated subfacies, O. borneensis layered galleries) and Colgate Members in stream cuts along Sand Creek.

Previous work.--Wilde (1983)

Site 2-3

Fig. 11

Location.--NW $\frac{1}{4}$, Sec. 2, T. 14 N., R. 55 E.

Remarks.--Trail City Member of the Fox Hills-Marmarth, Member of the Hell Creek Formation. Gyrochorte occurs in ferruginous mudstone ledges in the lower portion.

Previous work.--Butler (1980); Erdmann and Larsen (1934); Dobbin and Reeside (1929).

Site 2-4

(Iron Bluff)

Location.--NW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 10, T. 14 N., R. 55 E.

Remarks.--Pierre Formation through Hell Creek Formation (Little Beaver Creek Member) exposed; contorted bedding occurs in the Timber Lake; trough sets, 0.15-0.3-m-thick, even, nonparallel lower bounding surfaces, current direction to the southwest, indurated sand, occur in the top 8 m of the Colgate.

Previous work.--Dobbin and Reeside (1929); Thom and Dobbin (1924); Calvert (1912); Leonard (1906).

Site 2-5

Fig. 12

Location.--Sec. 10, 15, T. 14 N., R. 55 E.; road cuts along the road south to Baker.

Remarks.--Pierre Formation through Colgate member; Timber Lake

(hummocky facies) well exposed.

Site 2-6

Fig. 56

Location.--E $\frac{1}{2}$, Sec. 22, T. 14 N., R. 55 E.

Remarks.--Pierre Formation through Colgate Member; good exposures of the Trail City (including turbidites) and Timber Lake (hummocky facies).

Site 2-7

Location:--SE $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 13, T. 13 N., R. 55 E.

Remarks.--Pierre Formation through Colgate Member exposed; Pierre-Fox Hills contact well exposed.

Site 2-8

Location.--NW $\frac{1}{4}$, Sec. 32, T. 13 N., R. 56 E.

Remarks.--Pierre Formation through Timber Lake Member exposed; excellent outcrops of the upper Trail City (Rhizocorralium).

LOCATION 4

Meade County, South Dakota

Site 4-1

Location.--T. 8 N., R. 11 E.; cuts along the road from Fairpoint to U.S. 34.

Remarks.--Excellent exposures of the Timber Lake Member (hummocky bedding containing O. nodosa=units 11-14 of the Fairpoint Member of Pettyjohn 1967, p. 1364); large scale trough cross-bedding of the upper "Fairpoint" Member occurs to the north.

Previous work.--Pettyjohn (1967); Searight (1939)

Site 4-2

Location.--Cuts along the road from Red Owl to Stoneville.

Remarks.--Climbing ripples and large scale trough cross-bedding in the fine-medium sand of the Stoneville Coal facies, similar structures in the upper "Fairpoint" Member overlie the hummocky bedding at site 4-1.

Site 4-3

Location.--Road cuts along U.S. 34 from the junction of the road north to Marcus, east to Plainview.

Remarks.--Hummocky bedding exposed in the east, both hummocky and trough bedding in the western outcrops.

LOCATION 5

Iron Lightning, South Dakota

Site 5-1

Fig. 9

Location.--Sec. 33, T. 14 N., R. 19 E., Redelm NE quadrangle, Ziebach Co.

Remarks.--Type locality of the Iron Lightning Member; widespread exposure of the Bullhead and Colgate lithofacies.

Previous work.--Waage (1968, p. 132-134).

LOCATION 6

Little Eagle, South Dakota

Site 6-1

Location.--SW $\frac{1}{4}$, Sec. 26, T. 20 N., R. 26 E.; Little Eagle NW quadrangle, Corson, Co.; one mile north of the Grand River on U.S. 63.

Remarks.--Type locality of the Little Eagle lithofacies of the Trail City Member; hummocky beds (= units 5, 7, and 10 of Waage 1968, p. 85) interbedded with clayey silt and ovoid, fossiliferous, calcareous concretions.

Previous work.--Waage (1968, p. 84-86).

LOCATION 7

Missouri Valley of North Dakota

Site 7-1

(Crowghost Cemetery)

Fig. 10

Location.--C. Sec. 33, T. 134 N., R. 81 W.

Remarks.--Timber Lake Member of the Fox Hills Formation through the Huff Member of the Hell Creek Formation; excellent exposures of the Iron Lightning Member and the Fox Hills (Colgate lithofacies)- Hell Creek contact; Colgate lithofacies contain O. borneensis (?).

Previous work.--Carlson (1983); Frye (1967; p. 57-59); Laird and Mitchell (1942).

Location.--NW $\frac{1}{4}$, sec. 21, T. 134 N., R. 79 W.; cutbank at the mouth of the Cannonball River, just east of the bridge on N.D. 1806.

Remarks.--Timber Lake through Iron Lightning Members exposed; excellent outcrops of the Timber Lake Member (trough cross-bedded sand; O. nodosa forms A, B, and C).

Previous work.--Feldmann (1972, pl. 1, column 3).

APPENDIX A

Part 2

MEASURED SECTIONS, STUDY AREA

Study Area Measured Sections

The Fox Hills Formation is exposed at seven major outcrop sites in the study area; these are numbered 1 to 7 (north to south) and have a corresponding geographic designation (i.e., "Horse Creek" site). For each site, two or more described and measured outcrop sections appear; these are designated by the site number followed by a small letter, as in "4b". The sites are as follows (fig. 2, 71, 74):










Site 1	Little Beaver Creek	(a, b, c)
Site 2	North Creek	(a, b, c, d)
Site 3	Turbiville Bluff	(a, b)
Site 4	S-curve north	(a, b, c)
Site 5	S-curve east	(a, b, c)
Site 6	Horse Creek	(a, b, c, d, e, f)
Site 7	Sevenmile Creek	(a, b)

The study area corresponds to location 3 (fig. 1, 3, 59, 70) in the regional picture; however, the numerical prefix "3" is not used with these sites (i.e., 4b not 3-4b).

Both columns and written lithologic descriptions are provided: the written descriptions stress information on color, lithology, and detailed characterizations of sedimentary structures; the columns stress the succession and distribution of sedimentary structures, marker zones, and biota. The written descriptions

LEGEND


Sedimentary Structures


concretion	
cone-in-cone concretion	
hummock-form concretion	
finely interbedded	
mixed-massive	
wavy layer	
hummocky bedding	
trough cross-bedding	
scour and fill bedded	

Biota

root molds	
------------	--


Ophiomorpha

<u>O. borneensis</u>	
----------------------	--


<u>O. nodosa</u>	
------------------	---

(forms A and B)

Cosmorhapha

<u>fodinichnia</u> (unidentified)	
-----------------------------------	---

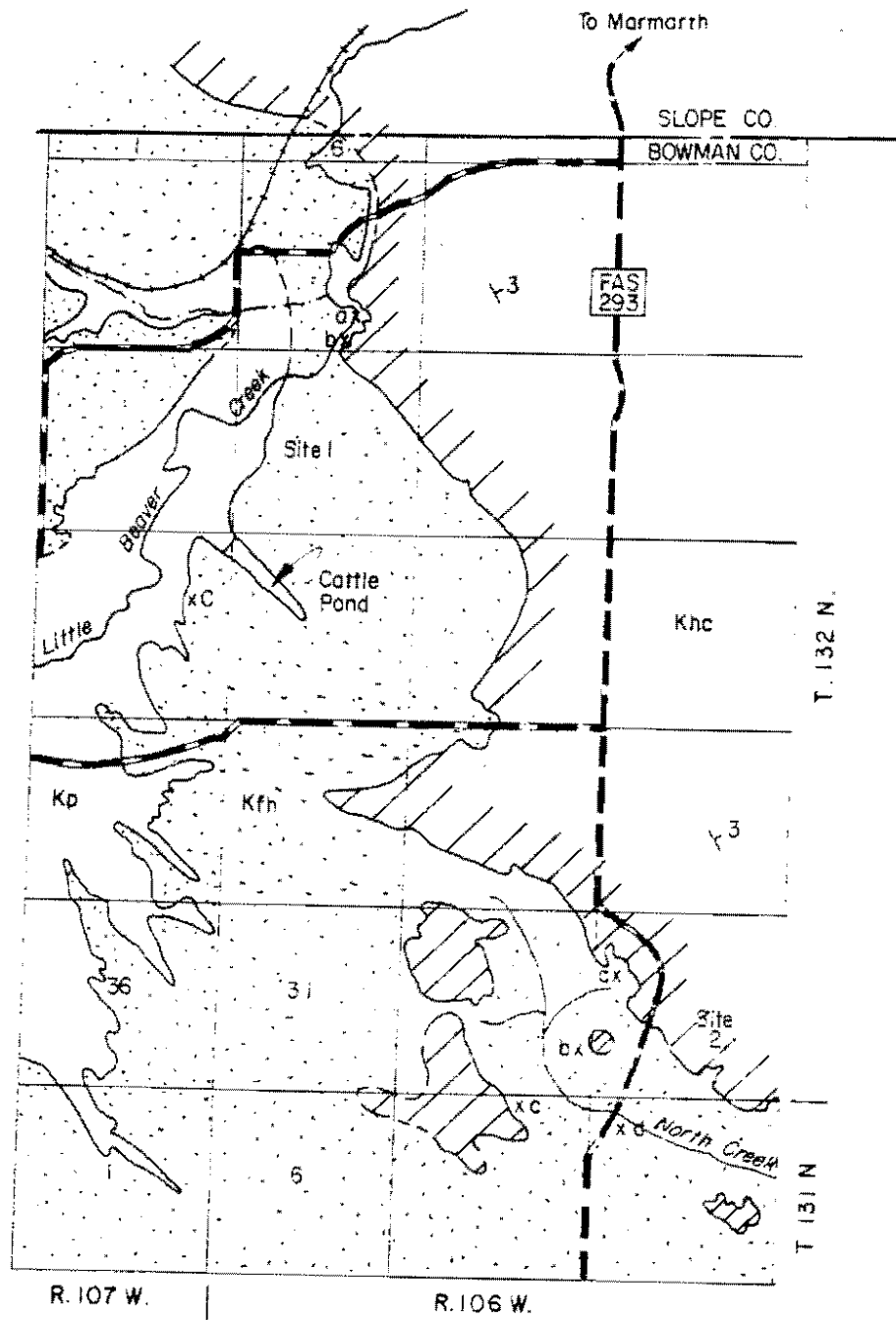
Other

Unit number (from written description)	
--	---

Sample horizon	
----------------	---

numbered from bottom to top. All measurements are in meters and are given only for that portion of the outcrop measured. The written descriptions are keyed to the columns by site numbers; the unit numbers used in the written description appear along side the column. Colors are given for weathered surfaces at outcrop.

Figure 67. Geologic map of the north half of the study area (modified from Erdmann and Larsen 1934). Sites 1 and 2 occur in this area.



SITE 1 (a-d)

Little Beaver Creek

Location.--Secs. 7, 18, 24, T. 132 N., R. 106 W.; Marmarth (1980) and Kid Creek (1973) quadrangles; west facing cutbanks along Little Beaver Creek; relief 40-50 m.

Remarks.--Pierre through Marmarth Member of the Hell Creek exposed; Pierre-Fox Hills contact exposed to the south at sites 1c and 1d; 33 lithologic samples taken at 1b.

Previous Work.--Leonard (1908, p. 44, pl. V); Stanton (1910, p. 182-3); Hares (1928, p. 17); Dobbin and Reeside (1929, p. 14-15); Brown (1939, pl. 62); Frye (1969, p. 61-62).

SITE 1a

SW $\frac{1}{4}$, NW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 7, T. 132 N., R. 106 W.

Fig. 32, 77

HELL CREEK FORMATION (MARMARTH MEMBER)

8. Sand, fine-medium; gray-orange (10YR 7/4); trough cross-bedded; concretions and indurated ledges (unit 14, site 1b).

TOTAL	14.0
	14.0

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

- | | |
|---|------|
| 7. Silty clay, carbonaceous; brown black; root molds common | 2.5 |
| 6. Sand, fine-medium, clayey; white-pale lavender; trough cross-bedded; root molds common (unit 11, site 1b). | 2.5 |
| 5. Silty clay, carbonaceous, brown-black. | 4.0 |
| 4. Sand, fine-medium; pale olive (10Y 6/2). | 1.5 |
| TOTAL | 10.5 |

Thickness of the Hell Creek
Formation Measured

(24.5)

FOX HILLS FORMATION (COLGATE MEMBER)

- | | |
|---|-----|
| 3. Sand, fine-medium, light olive gray (5Y 6/1); a single set of epsilon cross-bedding, carbonaceous sand and minic claystone pebble lag on the foresets; each foreset 0.5 m thick; foresets convex-up; erosional lower bounding surface, a 0.5-m-thick carbonaceous sand, continuous with the foresets, occurs at the top. | 4.0 |
| 2. Sand, fine-medium; pale olive (10Y 6/2); horizontal surfaces (wavy layers ?) define 0.5-m-thick beds containing small scale troughs and horizontal lamination. Erosional surface with minor relief at the base of the member. | 4.0 |
| TOTAL | 8.0 |

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

- | | |
|--|------|
| 1. Sand, fine-medium; light olive gray (5Y 6/1); hummocky bedded, amalgamated; <u>O. borneensis</u> occur 2 m above the creek level. | 2.0 |
| TOTAL | 12.0 |

Level of Little Beaver Creek

Thickness of the Fox Hills Formation Measured

(20.0)

SITE 1b

SW $\frac{1}{4}$, SW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 7, T. 132 N., R. 106 W.

Fig. 28, 29

HELL CREEK FORMATION (MARMARTH MEMBER)

- | | |
|---|------|
| 14. Sand, fine-medium; gray-orange (10YR 7/4); trough cross-bedded, concretions and indurated ledges (unit 8, site 1a). | 12.0 |
| TOTAL | 12.0 |

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

13. Silty clay, carbonaceous; gray	0.6
12. Silty clay, carbonaceous, brown-black, root molds common	2.0
11. Sand, fine-medium; clayey; white-pale lavender; trough cross-bedded, root molds common (unit 6, site 1a).	2.5
10. Silty clay; light gray (N 7)	2.0
9. Silty clay, carbonaceous; black-brown	0.4
8. Clay, gray, popcorn surface.	2.0
7. Sand, fine-medium; black-brown.	0.5
6. Sand, fine-medium, carbonaceous; gray; wavy layers at base.	1.6
5. Sand, fine-medium, carbonaceous (HCm); pale yellow brown; (10YR 6/2); massive appearance; leaves occur on irregular bedding planes; minor relief along erosional base.	1.5
TOTAL	13.1

Thickness of the Hell Creek Formation Measured (25.1)

FOX HILLS FORMATION (COLGATE MEMBER)

4. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1).	
b. Large scale trough cross bedding (1 X 3 m); carbonaceous material concentrated at lower bounding surfaces.	4.0
a. Scour and fill beds, 0.5 m thick, capped by wavy layers; erosional base marked by carbonaceous laminae and come-in-cone concretions; relief minor.	2.0
TOTAL	6.0

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

3. Sand, fine-very fine, moderate sorting; light olive gray (5Y 6/1) at the top, gray-orange (10YR 7/4) at the base; hummocky bedded, amalgamated; <u>O. borneensis</u> common.	12.0
2. Sand, very fine-fine, moderate sorting; gray orange (10YR 7/4); hummocky bedded (HFX), wavy layers cap hummocky beds as W zones.	4.0
1. Sand, very fine-fine, silty; light olive gray (5Y 6/1); interbedded with gray clay in wavy bedding or as hummocky L-sets (0.5 m by 3-10 m) encased in wavy bedding; L-sets have erosional bases, convex tops and have wavy ripples at the base and top; the lentils coalesce up-section.	2.0
TOTAL	18.0

Level of Little Beaver Creek
 Thickness of the Fox Hills Formation Measured (24.0)

SITE 1c

C., NW $\frac{1}{4}$, Sec. 24, T. 132 N., R. 107 W.

Fig. 40

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

6. Sand, fine to very fine, moderate sorting; light olive gray (5Y 6/1); hummocky bedded, amalgamated (?): grassed over, poorly exposed.	3.0
5. Sand, very fine-fine, moderate sorting; gray orange (10YR 7/4); hummocky bedded (HFX) overlain by W zones; poorly exposed except at the base.	4.0

SITE 2 (a-d)

North Creek

Location.--S $\frac{1}{2}$, Sec. 29; W $\frac{1}{2}$, Sec. 33; Sec. 32; T. 132 N., R. 106 W;
NW $\frac{1}{4}$, Sec. 4, T. 131 N., R. 106 W.; Kid Creek (1973)

Quadrangle; badlands along North Creek; relief 40 m.

Remarks.--Trail City Member of the Fox Hills through Marmarth
Member of the Hell Creek exposed; Pierre-Fox Hills contact
not exposed, but extensive exposure of the Hell Creek-Fox
Hills contact and the Colgate Member occurs; excellent
exposure of the Trail City-Timber Lake contact at 2d.

Previous Work.--Hares (1928, p. 18); Feldmann (1967; 1972, p. 24-25,
fig. 4, pl. 1); Frye (1969, figs. 3, 4); Carlson (1979, p. 10-12,
figs. 6, 7, pl. 2). Site 2d is the classic section where the
Pierre-Fox Hills contact on the south end of the anticline
has been most often described. (= Trail City-Timber Lake
Contact).

SITE 2a

SW $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 33, T. 132 N., R. 106 W.

Fig. 43, 45

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

3. Silty clay, sand, commonly carbonaceous; (un-
differentiated) shades of gray and brown; medium-
bedded, beds 1-3 m thick; root molds common. 12.0

Figure 68. Measured sections at site 1.

4. Sand, very fine-fine, light olive gray (5Y 6/1); interbedded as wave ripples with gray clay in wavy bedding or as hummocky lentils (0.5 m x 3-10 m) encased in wavy bedding.

TOTAL	<u>3.0</u> 10.0
-------	--------------------

FOX HILLS FORMATION (TRAIL CITY MEMBER)

3. Silt, sandy; light gray (N 5) and clay; medium gray (N 5); mixed- and mottled or thinly interbedded, a few silty sand beds at the top; hummocky bedded sandy silt beds, light gray, 0.5-m-thick occur at 6 m, 8.5 m and 10 m above the Pcm; the hummocky beds contain the trace fossils Cosmorhapee; O. nodosa, and unidentified fodinichnia.

7.0

2. Clay-silt interbeds, silt impregnated with yellow jarosite, bedding planes indistinct; TCjm marker.

TOTAL	<u>3.0</u> 10.0
-------	--------------------

Thickness of the Fox Hills Formation Measured	(20.0)
---	--------

PIERRE FORMATION

1. Clay, gray, some silty zones.

TOTAL	<u>3.0</u> 3.0
-------	-------------------

Level of the Pcm marker.

Thickness of the Pierre Formation Measured	(3.0)
--	-------

2. Sand, fine-medium, carbonaceous (HCm); pale yellow brown (10YR 1/4); massive,; leaves and carbonaceous material occur on irregular bedding surfaces; low angles foresets (?) also occur; erosional base gently undulatory, 0.5 m relief on the contact.

TOTAL	$\frac{0.4}{12.4}$
-------	--------------------

Thickness of the Hell Creek Formation
Measured

(12.4)

FOX HILLS FORMATION (COLGATE MEMBER)

1. Sand, fine-medium, poorly sorted; light, olive gray (5Y 6/1);
- b. massive appearance, structures obscured by carbonaceous root molds.
- a. large scale trough cross-bedding; sets are 0.5-1 m by 4-10 m.

0.5

TOTAL	$\frac{3.2}{3.7}$
-------	-------------------

Level of sand apron at the cliff base.

Thickness of the Fox Hills Formation
Measured

(3.7)

SITE 2b

W $\frac{1}{2}$, SE $\frac{1}{2}$, Sec. 32 and W $\frac{1}{2}$, SW $\frac{1}{2}$, Sec. 33, T. 132 N., R. 106 W.

Fig. 33, 34, 47, 61

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

6. Sand, fine-medium; light olive gray (5Y 6/1); as ripples in wavy bedding, drapes are gray bentonitic clay or carbonaceous mudstone.
7. Sand, fine-medium, slightly carbonaceous (HCm); pale yellow brown (10YR 7/4); minimal erosion at the base.

TOTAL	$\frac{0.4}{2.4}$
-------	-------------------

Thickness of the Hell Creek Formation
Measured

(2.4)

FOX HILLS FORMATION (COLGATE MEMBER)

4. Sand, fine-medium, poorly sorted, light olive gray (5Y 6/1)	1.5
d. Few structures visible; scour and fill bedding (?); minor fluting.	1.5
c. Trough cross-bedded, sets 0.2-0.3 m thick, even nonparallel bounding surfaces, foresets tangential, current direction to the west; wavy layers rare.	2.0
b. Trough cross-bedding, 0.3 m thick sets capped by wavy layers with carbonaceous or micaceous drapes; fluting is well developed.	3.0
a. Covered.	
TOTAL	<u>1.0</u> 7.5

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

3. Sand, fine-very fine; light olive gray (5Y 6/1); hummocky bedded, amalgamated; <u>O. nodosa</u> form A and B; poorly exposed at the base.	8.0
2. Covered; scattered hummock-form concretions; gray-orange (10YR 7/4).	10.0
1. Covered; gray (N 5) at the surface.	2.5
TOTAL	<u>20.5</u>

Level of North Creek.

Thickness of the Fox Hills Formation
Measured

(28.0)

SITE 2c

SW $\frac{1}{4}$, SE $\frac{1}{4}$, Sec. 32, T. 131 N., R. 106 W.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

4. Sand, fine-medium; light olive gray (5Y 6/1); cross-bedded.	20.0
3. Sand, carbonaceous; pale yellow brown (10YR 6/2); massive appearance, leaves and carbonaceous material occur on irregular laminae; =lower surface is erosional and slightly undulatory, relief of 0.5 m.	
TOTAL	<u>1.2</u> 21.2

Thickness of the Hell Creek Formation
Measured (21.2)

FOX HILLS FORMATION (COLGATE MEMBER)

2. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1).	
c. Massive appearance; structures obscured by carbonaceous root molds and partings.	1.5
b. Massive appearance; surface weathering obscures structures; scour and fill bedding visible.	7.5
a. Carbonaceous sand, as ripples in wavy bedding with carbonaceous drapes, or in massive layers.	
TOTAL	<u>3.0</u> 12.0

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

1. Sand, very fine-fine, moderately sorted; gray-orange (10YR 7/4); hummocky bedded, amalgamated; <u>0. borneensis</u> galleries common.	
TOTAL	<u>5.0</u> 5.0

Break in slope.

Thickness of the Fox Hills Formation
Measured

(17.0)

SITE 2d

NW $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 4, T. 131 N., R. 106 W.

Fig. 41, 48

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

- | | |
|---|--------------------|
| 5. Sand, fine-very fine, moderately sorted; light olive gray (5Y 6/1); hummocky bedded, amalgamated; <u>O. borneensis</u> present. | 3.5 |
| 4. Sand, very fine-fine, moderately sorted; gray-orange (10YR 7/4); Hummocky bedded, (HFX) beds 1-2 m thick overlain by W zones, multiple L-sets occur; <u>O. nodosa</u> present. | 6.0 |
| 3. Sand, silty-silt, sandy, poorly sorted; light gray (N 7). | |
| b. Hummocky bedded, (HbFbXb) beds 0.3-0.5 m thick overlain by W zones, single L-set layers; <u>O. nodosa</u> common. | 1.2 |
| a. Concretion zone (TLcm); ovoid 0.3-0.5 m diameter; mixed, massive; remnant hummocky lamination; <u>O. nodosa</u> and unidentified <u>fodinichnia</u> occur. | |
| TOTAL | <u>0.5</u>
11.2 |

FOX HILLS FORMATION (TRAIL CITY MEMBER)

- | | |
|---|-----|
| 2. Silt and clay, light gray (N 7): interbedded or mixed and mottled. | 5.0 |
|---|-----|

1. Silt, light gray (N 7); contains 1-2 cm thick clay and sandy silt layers, bedding planes gradational; basal 2 m covered.

TOTAL	<u>5.0</u> 10.0
-------	--------------------

Level of North Creek

Thickness of Fox Hills Formation
Measured

(21.2)

Figure 69. Measured sections at site 2.

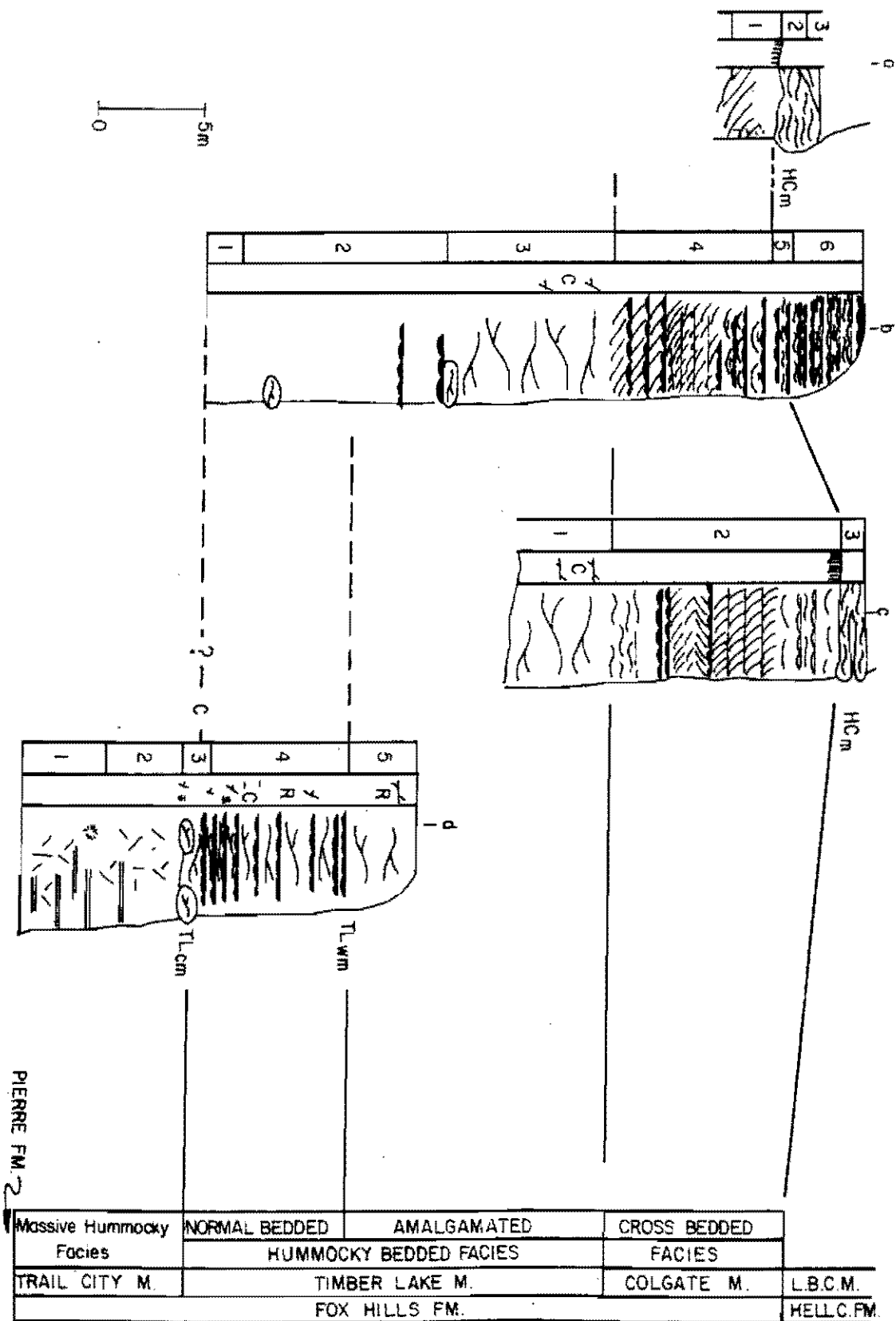
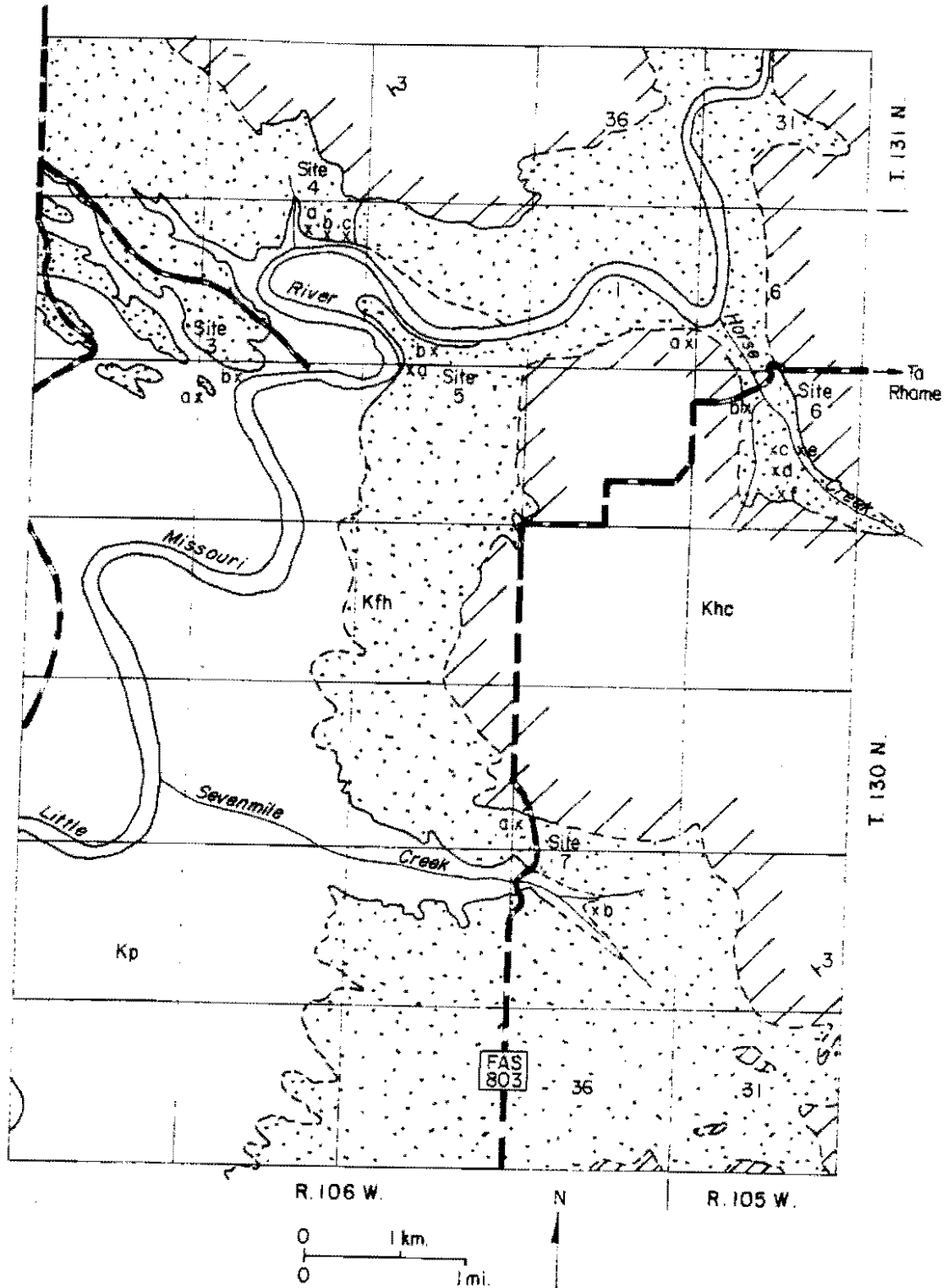


Figure 70. Geologic map of the south half of the study area (modified from Erdmann and Larsen 1945). Sites 3, 4, 5, 6, and 7 occur in this area.



SITE 3 (a, b)

Turbiville Bluff

Location.--N $\frac{1}{2}$, NW $\frac{1}{2}$, Sec. 10, T. 130 N., R. 106 W.; Cedar Ridge (1973). Quadrangle; bluffs on west side of the Little Missouri River, on the Turbiville farms; relief 40 m.

Remarks.--Pierre through Timber Lake Member exposed; excellent exposures of the Pierre-Fox Hills and Trail City-Timber Lake contacts.

SITE 3a

SW $\frac{1}{4}$, NW $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 10, T. 130 N., R. 105 W.
Alluvium.

FOX HILLS FORMATION (TRAIL CITY MEMBER)

2. Silt (gray, N 5) and clay (gray, N 7) interbedded or mixed and mottled.

TOTAL

$$\frac{7.5}{7.5}$$

Thickness of the Fox Hills Formation Measured

(7.5)

PIERRE FORMATION

1. Clay; gray (N 7); selenite crystals at the surface; cone-in-cone concretions, 0.15 m diameter (Pcm) at base.

TOTAL

$$\frac{1.5}{1.5}$$

Level of the Pcm.

Thickness of Pierre Formation Measured

(1.5)

SITE 3b

NW ¼, NW ¼, Sec. 10, T. 130 N., R. 106 W.

Soil horizon.

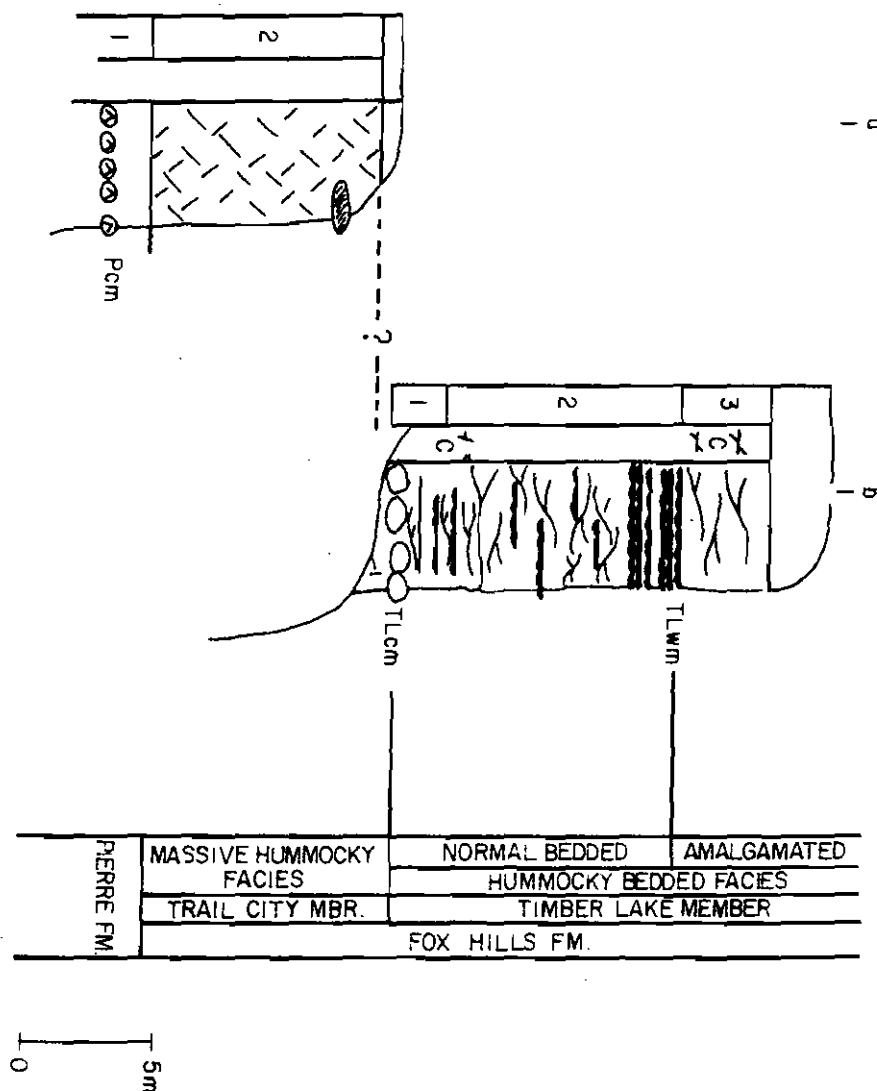
FOX HILLS FORMATION (TIMBER LAKE MEMBER)

- | | |
|--|-------|
| 3. Sand, very fine-fine, moderate sorting; light olive gray (5Y 6/1); hummocky bedded, amalgamated; <u>O. borneensis</u> layered galleries. | 3.0 |
| 2. Sand, very fine-fine, moderately sorted; gray orange (10YR 7/4); | |
| c. Wavy bedding (<u>TLwm</u>); hummocky bed, 0.5-m-thick, in the middle. | 2.0 |
| b. Hummocky bedded, discontinuous ferruginous W zones. | 3.0 |
| a. Hummocky bedded, normal bedded (HFX) 0.5-1-m-thick, multiple L-set layers per H zone; overlain by W zones; undulating W zones preserve hummocky deposurface topography. | 5.5 |
| 1. Sand, silty-sandy silt; poorly sorted; greenish gray (5YR 6/1); | |
| b. Hummocky bedded, normal-bedded (HFX), 0.3-0.5-m-thick, single L-set layer per H zone; overlain by W zones; zones of intense bioturbation containing <u>O. nodosa</u> and unidentified fodinichnia that become less common upward. | 3.0 |
| a. Concretion zone (<u>TLcm</u>), concretions ovoid 0.5 m diameter; mixed, mottled. | 0.5 |
| | TOTAL |
| | 16.5 |

Level of the TLcmThickness of the Fox Hills Formation
Measured

(16.5)

Figure 71. Measured sections at site 3.



SITE 4 (a-c)

S-curve north

Location.--N $\frac{1}{2}$, NE $\frac{1}{2}$, Sec. 3, T. 130 N., R. 106 W.; Cedar Range (1973). Quadrangle; south-facing bluffs on the Little Missouri River; relief 50 m.

Remarks.--Pierre-through Little Beaver Creek Member of the Hell Creek; excellent exposures of the Colgate channel facies; section below the upper Timber Lake covered by talus at 4a and 4b; poor exposure of the Pierre-Fox Hills contact and the Pierre Formation; poor exposure of the Trail City Member; 33 lithologic samples taken from 4a and 4c.

SITE 4a

NE $\frac{1}{2}$, Sec. 3, T. 103 N., R. 106 W.

Fig. 31

Top of bluff.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

5. Sand, fine-medium; yellow gray (5Y 6/4).	10.0
4. Sand and clay, carbonaceous; red brown; interbedded.	2.5
3. Sand, carbonaceous (HCm ?); pale yellow brown (10YR 6/2).	
TOTAL	<u>1.0</u> 13.5

Thickness of the Hell Creek Formation
Measured

(13.5)

FOX HILLS FORMATION (COLGATE MEMBER)

2. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1);	
d. Trough cross-bedded, large scale sets 0.3-1-m-thick; tangential laminae, carbonaceous concentrations in foreset toes accentuate lower bounding surfaces; current direction to the south; <u>O.</u> <u>borneensis</u> rare and isolated.	6.5
c. Claystone cobble lag along basal planar erosional surface.	0.15
b. Trough cross bedding; sets 0.3-m- thick; claystone pebble lags on foresets and lower bounding surfaces; boulders (0.3 m diameter) of carbonaceous sand (HCm(?)) present.	1.0
a. Trough cross bedding, sets 0.3-m-thick.	1.0
TOTAL	<u>8.65</u>

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

1. Sand, very fine-fine, moderate sorting; light olive gray (5Y 6/1);	
e. Wavy bedding (<u>TLfm</u>); ferruginous mudstone drapes.	1.0
d. Hummocky bedded, amalgamated; <u>O. borneensis</u> , tightly packed layered galleries.	3.5
c. Hummocky bedded, amalgamated; barren.	1.5
b. Hummocky bedded, amalgamated; <u>O.</u> <u>borneensis</u> , tightly packed layered galleries.	0.8

- a. Hummocky bedded, amalgamated;
barren.

TOTAL $\frac{2.1}{8.9}$

Top of talus.

Thickness of the Fox Hills Formation
Measured

(17.55)

SITE 4b

NE $\frac{1}{4}$, Sec. 3, T. 130 N., R. 106 W.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

3. Sand, fine-medium, carbonaceous (HCm);
pale yellow brown (10YR 6/2); inter-
bedded with light olive gray sand.

TOTAL $\frac{1.0}{1.0}$

Thickness of the Hell Creek Formation
Measured

(1.0)

FOX HILLS FORMATION (COLGATE MEMBER)

2. Sand, fine-medium, poorly sorted,
light olive gray (5Y 6/1); large
scale trough cross bedding; even
nonparallel bounding surfaces;
sets 0.3-0.6-m-thick,
exceptional sets 1.5-m-thick;
lower bounding surfaces and
foresets accentuated by
carbonaceous material; current
direction to the south.

TOTAL $\frac{9.0}{9.0}$

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

1. Sand, fine-very fine, moderately
sorted; light olive gray (5Y 6/1);
- b. Wavy bedding (TLfm);
ferruginous mudstone drapes;
base erosional; 0.5 m ripple period.

1.0

- a. Hummocky bedded, amalgamated; O. borneensis, tightly packed galleries.

TOTAL

3.0
4.0

Top of talus.

Thickness of the Fox Hills Formation
Measured

(13.0)

SITE 4c

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

4. Sand, very fine-fine, moderately sorted;
light olive gray (5Y 6/1);
 - b. Wavy bedded (TLfm); ferruginous
mudstone drapes. 1.0
 - a. Hummocky bedded, amalgamated, W
cutouts common at the base; O. borneensis layered galleries
common. 7.0
3. Sand, fine-very fine, poorly sorted,
gray-orange (10YR 7/4);
 - c. Hummocky bedded, normal bedded;
ferruginous W zones, W cut-
outs common upward; O. borneensis
layered galleries common. 3.0
 - b. Wavy bedded. 1.0
 - a. Hummocky bedded, normal bedded
(HFX) 0.3-m-thick overlain by
W zones, O. nodosa present. 7.0
2. Sand, very fine, silty or sandy silt;
poor sorting; gray (N 7):
 - b. Hummocky bedded, normal bedded (HFX)
0.3-0.6-m-thick (?) overlain by a
single clay drape; O. nodosa present;
poorly exposed. 2.0

- a. Concretion zone (TLcm); concretions
 ovoid 0.5 m diameter; mixed and
 massive, remnant hummocky laminae.

TOTAL $\frac{0.5}{20.5}$

FOX HILLS FORMATION (TRAIL CITY MEMBER)

1. Silt and clay; gray (N 5); mixed,
 mottled or finely interbedded;
 poorly exposed, lower two thirds
 covered by talus.

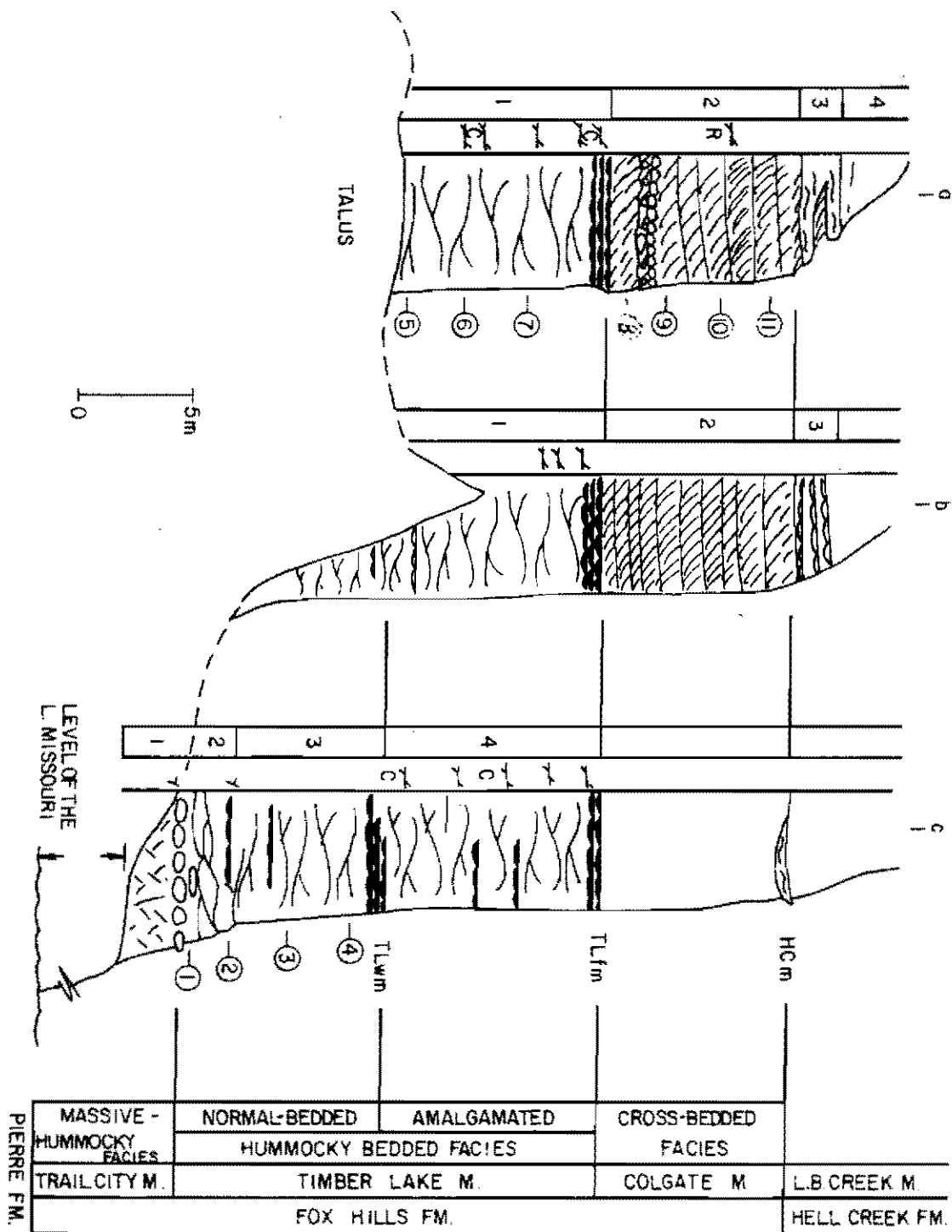
TOTAL $\frac{9.0}{9.0}$

Level of the Little Missouri River.

Thickness of the Fox Hills Formation
 Measured

(29.5)

Figure 72. Measured sections at site 4.



SITE 5 (a,b)

S-curve east

Location.--S $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 2, T. 130 N., R. 106 W.; Cedar Ridge (1973) Quadrangle; bluffs and cutbanks along the south bank of the Little Missouri River; relief 35 m.

Remarks.--Pierre through Timber Lake Member exposed, capped by Pleistocene terrace gravel; excellent exposure of the Trail City-Timber Lake contact, hummocky bedding, and bioturbation structures.

Previous Work.--Hares (1928, p. 18).

SITE 5a

SW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 2, T. 130 N., R. 106 W.

Fig. 62, 83

Top of Bluff (Terrace Gravel)

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

5. Sand, fine-very fine, moderately sorted; light olive gray (5Y 6/1); hummocky bedded, amalgamated.

4.0

4. Sand, fine-very fine, moderately sorted; gray orange (10YR 7/4); hummocky bedded, discontinuous ferruginous w. zones; O. borneensis layered galleries.

7.0

3. Sand, very fine-fine, moderately sorted; gray orange (10YR 7/4);
 - b. Wavy bedded (TLwm); continuous outcrop wide for over 0.5 km. 1.2
 - a. Hummocky bedded, normal bedded (HFX) 0.5-1-m-thick, single or multiple L-set layers per H zone; overlain by W zones; O. nodosa rare; water escape structures in H zones; lower contact scalloped hummocky scour. 5.0
 2. Sand, very fine, silty, poorly sorted, or sandy silt; gray olive (10Y 8/2);
 - b. Hummocky bedding or lamination alternates with zones of intense bioturbation (O. nodosa, unidentified fodinichnia). 1.5
 - a. Concretion zone (TLcm); concretions ovoid 0.5-1-m-diameter; mixed, massive; O. nodosa, Thalassinidea (?) 1.0
- TOTAL 19.7

FOX HILLS FORMATION (TRAIL CITY MEMBER)

1. Silt, sandy silt and clay; gray to light gray (N 5); mixed, mottled or finely interbedded; lower half covered by talus.
- TOTAL 9.0
9.0

Level of the Little Missouri River

Thickness of the Fox Hills Formation Measured

(28.7)

SITE 5b

SE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 2, T. 130 N., R. 106 W.

Fig. 49

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

4. Sand, fine-very fine, moderately sorted; light olive gray; hummocky bedded, amalgamated. 3.5

3. Sand, fine-very fine, poorly sorted;
gray-orange (10YR 7/4);
 - c. Hummocky bedded, normal bedded;
Ferruginous W zones are dis-
continuous; O. nodosa common
below W zones 5.5
 - b. Wavy bedded. 1.8
 - a. Hummocky bedded, normal bedded
(HFX) 0.5-1-m-thick (up to 2 m)
single or multiple L-set layers
per H set; overlain by W zones;
undulating W zones preserve the
hummocky deposurface; O. nodosa
present; lower contact scalloped
hummocky scour. 7.5
 2. Sand, very fine, silty, or sandy mud;
greenish gray (5GY 6/1);
 - b. Hummocky bedding or lamination
alternate with zones of intense
bioturbation (O. nodosa,
unidentified fodichinia). 1.8
 - a. Concretion zone (TLcm); concretions
ovoid 0.5-1-m-diameter;
mixed, massive.
- TOTAL 1.0
21.1

FOX HILLS FORMATION (TRAIL CITY MEMBER)

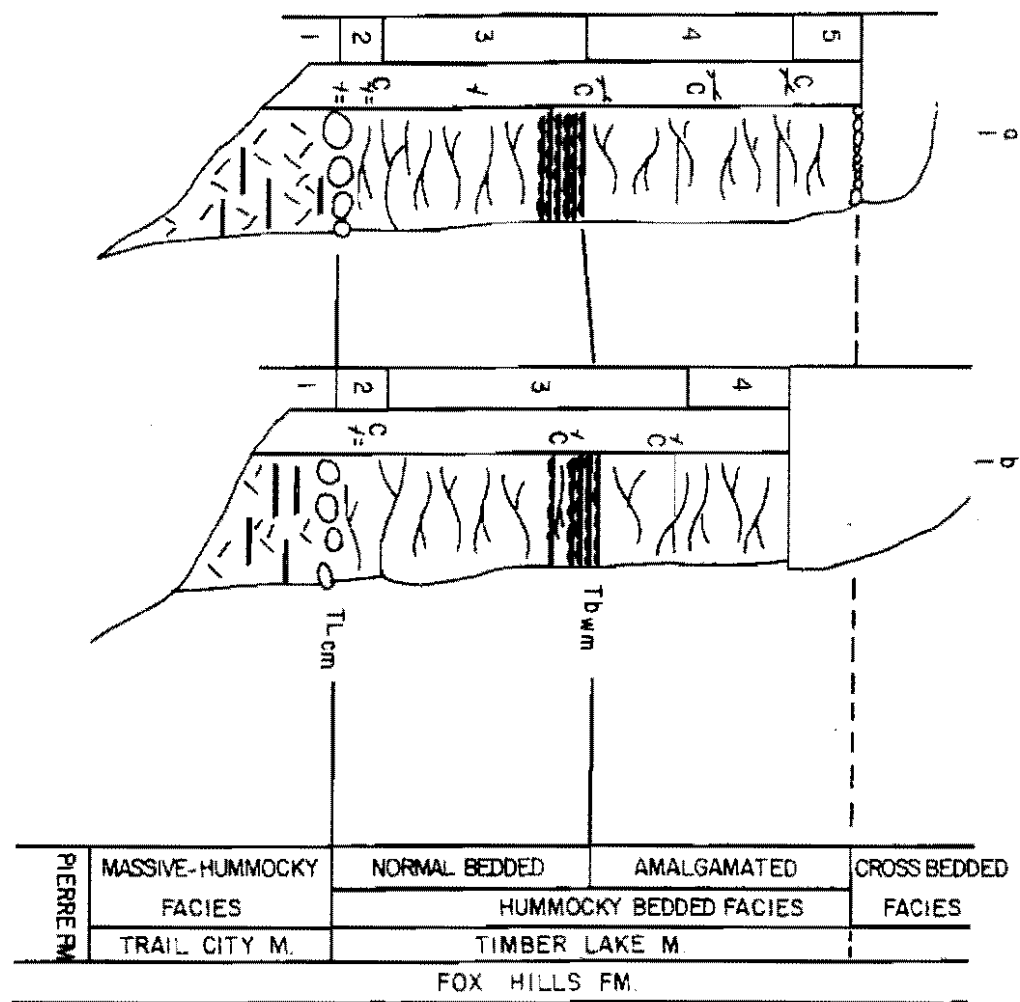
1. Silt, clay and sandy mud,
(gray-light gray (N 7); finely
interbedded or mixed and
mottled; lower half covered by
talus.
- TOTAL 9.0
9.0

Level of the Little Missouri River

Thickness of the Fox Hills Formation
Measured

(30.1)

Figure 73. Measured sections at site 5.



5m
10

SITE 6 (a-f)

Horse Creek

Location.--S $\frac{1}{2}$, SW $\frac{1}{2}$, NW $\frac{1}{2}$, SW $\frac{1}{2}$, Sec. 6 and 7, T. 130 N., R. 105

W.; Mud Buttes (1973) Quadrangle; cutbank on the south side of the Little Missouri, and south in the badlands along Horse Creek.

Remarks.--Timber Lake through the Marmarth Member of the Hell Creek exposed; widespread exposures of the Timber Lake-Colgate and Colgate-Hell Creek contacts; excellent exposures of Colgate structures.

SITE 6a

S $\frac{1}{2}$, S $\frac{1}{2}$, SW $\frac{1}{2}$, NW $\frac{1}{2}$, SW $\frac{1}{2}$, Sec. 6, T. 130 N., R. 105 W.

Top of Bluff.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

- | | |
|--|-----|
| 9. Silty clay; white gray. | 4.0 |
| 8. Silty clay; dark gray; popcorn surface. | 3.0 |
| 7. Sand, carbonaceous; pale yellow brown (10YR 6/2); massive; undulating base. | 1.0 |
| 6. Sand, fine-medium, poorly sorted; pale olive (10YR 6/2); single set of large scale foresets (epsilon (?) cross bedding), dipping 15-20° southwest, carbonaceous material concentrated at the tangential forset toes and along the lower bounding surface. | 2.0 |

5. Sand, fine-medium, poorly sorted; light olive-gray (5Y 6/1); large scale trough cross bedding; 0.3-0.6-m-thick, up to 30 m wide; carbonaceous material at the tangential forset toes accentuates the lower bounding surface; concretions containing current ripples are common toward the center of Sec. 6.	10.0
4. Sand, fine-medium, poorly sorted; carbonaceous (HCm); pale yellow brown (10YR 6/2); lenticular; trough cross bedded.	<u>1.0</u>
TOTAL	21.0
Thickness of the Hell Creek Formation Measured	(21.0)

FOX HILLS FORMATION (COLGATE MEMBER)

3. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1); trough cross bedded; poorly exposed.	<u>6.0</u>
TOTAL	6.0

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

2. Sand, fine-very fine, moderate sorting; light olive gray (5Y 6/1); hummocky bedded, amalgamated; <u>O. borneensis</u> layered galleries.	5.0
1. Sand, fine-very fine, poorly sorted; gray orange (10YR 7/4); hummocky bedded, discontinuous ferruginous W. zones; <u>O. borneensis</u> common.	<u>7.0</u>
TOTAL	12.0

Level of the Little Missouri River.

Thickness of the Fox Hills Formation Measured (18.0)

SITE 6b

SW $\frac{1}{4}$, NE $\frac{1}{4}$, NW $\frac{1}{4}$, Sec. 6, T. 130 N., R. 105 W.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

3. Sand, fine-medium, carbonaceous; pale yellow brown (10YR 6/2); trough cross

bedded, single set, large scale 0.5-2-m-thick; basal contact uneven and erosional, cutting into the underlying Colgate Member.

TOTAL $\frac{2.0}{2.0}$

Thickness of the Hell Creek Formation
Measured

(2.0)

FOX HILLS FORMATION (COLGATE MEMBER)

2. Sand, fine-medium, poorly sorted, light olive gray (5Y 6/1)

b. Tabular beds, 0.5-m-thick, bounded by carbonaceous wavy layers and containing small scale trough cross bedded and horizontal laminae. Root molds common at the top.

3.5

a. Large scale trough cross bedding.

TOTAL $\frac{2.0}{5.5}$

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

1. Sand, fine-very fine, moderate sorting; light olive gray (5Y 6/1).

b. Wavy bedded (TLfm); ferruginous mudstone drapes.

0.6

a. Hummocky bedded, amalgamated; O. borneensis tiered galleries.

TOTAL $\frac{9.0}{9.6}$

Level of Horse Creek.

Thickness of the Fox Hills Formation
Measured

(15.1)

SITE 6c

SE $\frac{1}{4}$, NW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 7, T. 130 N., R. 105 W.

Fig. 81

Top of bluff.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

6. Unit 5 at 6e.	1.8
5. Unit 4 at 6e.	2.7
4. Unit 3 at 6e.	3.0
3. Sand, fine-medium, carbonaceous (HCm); pale yellow brown (10YR 6/2); alternate with pale olive sand; all trough cross bedded; contact chosen at the major bed in the zone.	
TOTAL	<u>1.0</u> 8.5

Thickness of the Hell Creek Formation
Measured

(8.5)

FOX HILLS FORMATION (COLGATE MEMBER)

2. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1).	
d. Tabular beds, 0.15-m-thick capped by carbonaceous wavy layers and containing small scale trough beds in horizontal lamination (as at 6e).	2.5
c. Large scale trough cross bedding (as at 6e).	2.0
b. Wavy layer; continuous outcrop wide.	0.2
a. Structures obscured by fluted surface; carbonaceous wavy layers and partings; <u>O. borneensis</u> present.	
TOTAL	<u>4.0</u> 8.7

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

1. Sand, fine-very fine, moderate sorting; hummocky bedded, amalgamated.	
b. Light olive gray (5Y 6/1) <u>O. borneensis</u> .	3.0

- a. Gray-orange (10YR 7/4); 0.
borneensis common in layered
 galleries; orange tints occur
 in proximity to ferruginous W
 zones and ophiomorpha.

TOTAL	$\frac{4.0}{7.0}$
-------	-------------------

Level of Horse Creek

Thickness of the Fox Hills Formation
 Measured

(15.7)

SITE 6d

NW $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 7, T 130 N., R. 105 W.

Fig. 37, 46

Top of bluff.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

- | | |
|--|-----|
| 5. Silty clay; gray olive (10YR 4/2); popcorn surface; concretions at the base. | 1.8 |
| 4. Sand, interbedded with carbonaceous sand; (light gray (N 5)). | 2.7 |
| 3. Sand; light olive gray (5Y 6/1); large scale trough cross bedding, carbonaceous material on forsets and lower bounding surfaces; could be a continuation of (2). | 3.0 |
| 2. Sand, fine-medium, carbonaceous (HCm); pale yellow brown (10YR 6/2); trough cross bedded, single set of large scale forsets; irregular erosional base, scalloped in broad troughs; thickens with up to 2 m of Colgate removed eastward toward 6c. | |

TOTAL	$\frac{1.0}{8.5}$
-------	-------------------

Thickness of the Hell Creek
 Formation Measured

(8.5)

FOX HILLS FORMATION (COLGATE MEMBER)

- | | |
|---|-------|
| 1. Sand, fine-medium, poorly sorted;
light olive gray (5Y 6/1). | |
| d. Tabular beds, 0.15-m-thick capped
by carbonaceous wavy layers and
containing small scale trough
bedding and horizontal lamination;
irregular upper contact due to Hell
Creek erosion, most of the unit is
removed to the east. | 2.0 |
| c. Two large scale trough cross-bed
sets (1 m overlain by 0.4 m) | 1.4 |
| b. Wavy layer; an outcrop wide layer. | 0.1 |
| a. Trough cross-beds, 0.3-m-thick;
wavy layers are cut out; <u>O.</u>
<u>borneensis</u> present. | 1.1 |
| | <hr/> |
| | 4.2 |
| | TOTAL |

Level of sand apron.

Thickness of the Fox Hills Formation
Measured. (4.2)

SITE 6e

SW $\frac{1}{4}$, SW $\frac{1}{4}$, NE $\frac{1}{4}$, Sec. 7, T. 130 N., R. 105 W.

Fig. 35, 36, 42

Top of Bluff.

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

3. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1); 5 layers, 3-5-m-thick each, containing large-very large scale trough bedding, epsilon bedding; carbonaceous material on forsets and lower bounding surfaces; the lower contact is sharp, erosional, and undulating, with 2-4 m of relief on the underlying

Colgate; HCM absent.

TOTAL

$$\frac{17.0}{17.0}$$
Thickness of the Hell Creek Formation
Measured.

(17.0)

FOX HILLS FORMATION (COLGATE MEMBER)

2. Sand, very fine-fine, moderate sorting;
light olive gray (5Y 6/1); small scale
troughs occur associated with horizontal
laminae, erosional ripples, member is
variable in thickness (2-4 m) due to Hell
Creek erosion.

TOTAL

$$\frac{4.0}{4.0}$$

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

1. Sand, very fine-fine, moderate
sorting; light olive gray (5Y 6/1)
- b. Wavy bedded (TLfm); ferruginous
mudstone drapes.
- a. Hummocky bedded, amalgamated; O.
borneensis layered galleries.

TOTAL

$$\frac{1.3}{2.0}$$

3.3

Level of Horse Creek.

Thickness of the Fox Hills Formation
Measured.

(7.3)

SITE 6f

N $\frac{1}{2}$, NE $\frac{1}{4}$, SE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 7. T. 130 N., R. 105 W.

Fig. 44

HELL CREEK FORMATION (MARMARTH MEMBER) (?)

4. Sand, fine-medium, gray-orange
(10YR 7/4); trough cross-bedded.

TOTAL

$$\frac{4.5}{4.5}$$

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

3. Sand, light gray, stacked tabular layers (6), each 1-3-m-thick, each consisting of: containing trough and epsilon bedding (0.6-2.6-m-thick), capped by carbonaceous sand and gray silty clay with popcorn surface (0.6 m). 12.8

2. Sand, fine-medium, carbonaceous (HCm); pale yellow brown (10YR 6/2); leaves and carbonaceous material along irregular bedding planes; basal contact erosional, minor relief.

TOTAL $\frac{0.5}{13.3}$

Thickness of the Hell Creek
Formation Measured

(17.8)

FOX HILLS FORMATION (COLGATE MEMBER)

1. Sand, fine-medium, poorly sorted; light olive gray (5Y 6/1).
- b. Tabular beds, 0.15-m-thick, capped by carbonaceous wavy layers; root molds common, structures obscured by root molds. 1.2
- a. Trough cross-bedding (0.15-0.4-m-thick); even, horizontal lower bounding surfaces; minor horizontal lamination and wavy layers.

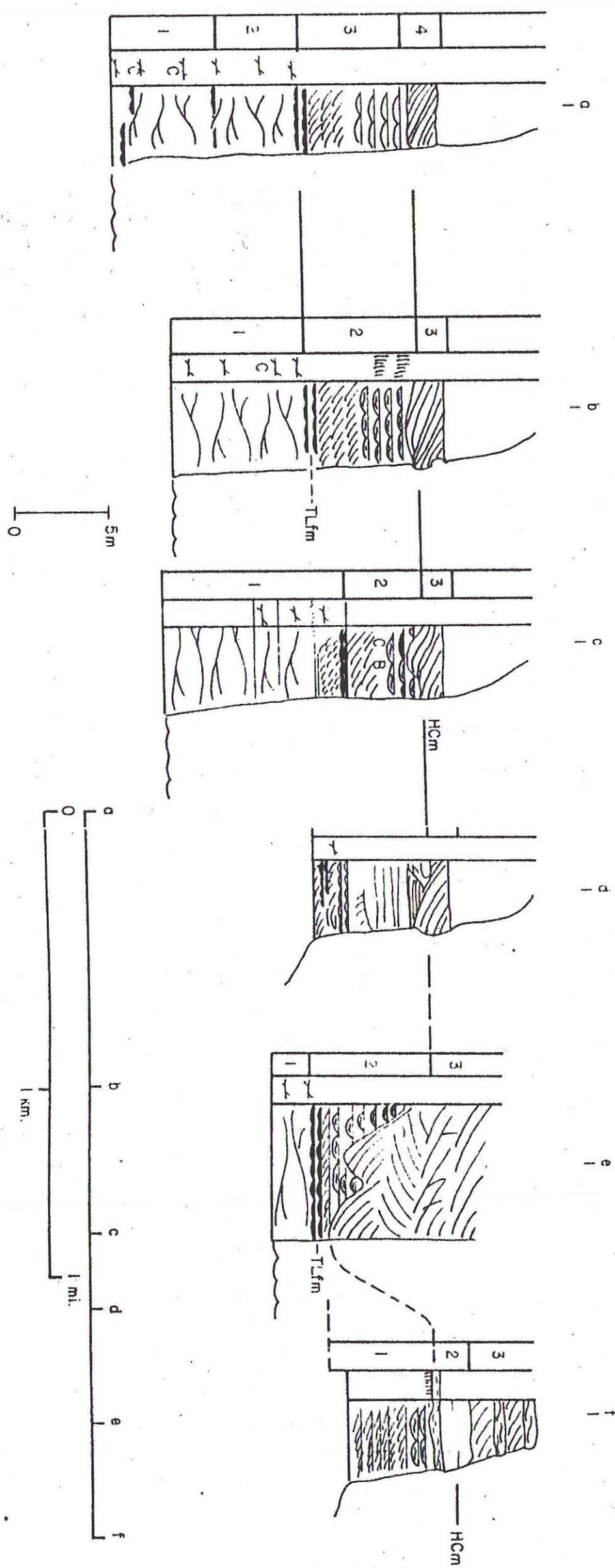
TOTAL $\frac{4.0}{5.2}$

Level of sand apron.

Thickness of the Fox Hills Formation Measured

(5.2)

Figure 74. Measured sections at site 6.



AMALGAMATED SUBFACIES	CROSS BEDDED FACIES	
TIMBER LAKE M.	COLGATE M.	L. BEAVER CREEK MBR.
FOX HILLS FM		HELL CREEK FM.

SITE 7 (a, b)

Sevenmile Creek

Location.--SW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 24 and Cent., Sec. 25, T. 103 N.,
R. 106 W.; Cedar Creek (1973) Quadrangle; bluffs along
Sevenmile Creek; relief 40 m.

Remarks.--Trail City through Little Beaver Creek Member of the
Hell Creek exposed; 33 lithologic samples taken.

SITE 7a

SW $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 24, T. 130 N., RR. 106 W.

Fig. 52

HELL CREEK FORMATION (LITTLE BEAVER CREEK MEMBER)

9. Sand, very fine, silty; light gray	1.0
8. Silty clay; weathers green-gray; popcorn surface.	1.8
7. Silty sand and carbonaceous clay; weathers white; finely interbedded; root molds common.	2.3
6. Silty clay, carbonaceous; brown	0.3
5. Silty clay; green gray.	0.8
4. Silt and carbonaceous clay; weathers white; finely interbedded.	0.5
3. Sand, fine-medium, poorly sorted, carbonaceous (HCm); pale yellow brown (10YR 6/2); massive appearance; leaves and carbonaceous material on irregular bedding planes.	
TOTAL	$\frac{0.5}{7.2}$

Thickness of the Hell Creek Formation
Measured

(7.2)

FOX HILLS FORMATION (COLGATE MEMBER)

- | | |
|--|-------|
| 2. Sand, fine-medium, poorly sorted;
light olive gray (5Y 6/1); surfaces
fluted; | |
| c. Low angle clayey foresets
(epsilon cross-bedding ?)
root molds common; lower contact
erosional. | 1.2 |
| b. Tabular beds, 0.5-m-thick capped
by carbonaceous wavy layers and
containing small scale trough
cross bedding in horizontal
laminae. | 4.9 |
| a. Trough cross bedding, 0.3-m-thick
sets, tangential foresets with
carbonaceous toes; erosional, even,
nonparallel, bounding surfaces;
basal contact erosional. | 2.0 |
| | <hr/> |
| TOTAL | 8.1 |

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

- | | |
|---|-------|
| 1. Sand, fine-very fine, moderate
sorting; light olive gray (5y 6/1);
surfaces fluted; | |
| b. Wavy bedded (TLfm); ferruginous
mudstone drapes over wave (?)
ripples; discontinuous, cut out;
<u>O. borneensis</u> gallery layers in
ripples and a single gallery
layer on the upper surface; <u>O.</u>
<u>borneensis</u> and hummocky beds and
abruptly at the horizon of the
upper surface of the TLfm. | 1.0 |
| a. Hummocky bedded, amalgamated; <u>O.</u>
<u>borneensis</u> gallery layers common. | 4.5 |
| | <hr/> |
| TOTAL | 5.5 |

Level of flattened gradient in arroyo.

Thickness of Fox Hills Formation
Measured

(13.6)

SITE 7b

SE $\frac{1}{4}$, SW $\frac{1}{4}$, Sec. 25, T. 130 N., R. 106 W.

Fig. 50

Alluvium

FOX HILLS FORMATION (COLGATE MEMBER)

4. Sand, fine-medium, poorly sorted;
light olive gray (5Y 6/1);
carbonaceous partings; poorly
exposed remnant, weathering
obscures structures.

TOTAL

$\frac{2.5}{2.5}$

FOX HILLS FORMATION (TIMBER LAKE MEMBER)

3. Sand, very fine-fine, moderate
sorting; light olive gray
(5Y 6/1);
- b. Wavy bedded (TLfm);
ferruginous drapes. 0.8
- a. Hummocky bedded, amalgamated;
O. borneensis layered galleries. 6.0
2. Sand, very fine-fine, poor sorting;
gray orange (10YR 7/4);
- d. Wavy bedded (TLwm). 2.0
- c. Hummocky bedded, normal bedded
(HFX) overlain by ferruginous W
zones, often cut out; O.
nodosa present. 6.0
- b. Wavy bedded. 2.2

- a. Hummocky bedded, normal bedded (HbFbXb) 0.6-m-thick (up to 1 m) single or multiple L-sets per H zone; overlain by W zones; 0. nodosa common; basal contact scalloped hummocky erosional surface.

2.0

1. Sand, very fine, silty, poor sorting; greenish-gray (5GY 6/1); hummocky bedded, normal bedded (HbFbXb) 0.3-0.5-m-thick, single L-set layers per H zone; overlain by a single clay drape; 0. nodosa common; base below stream level.

TOTAL

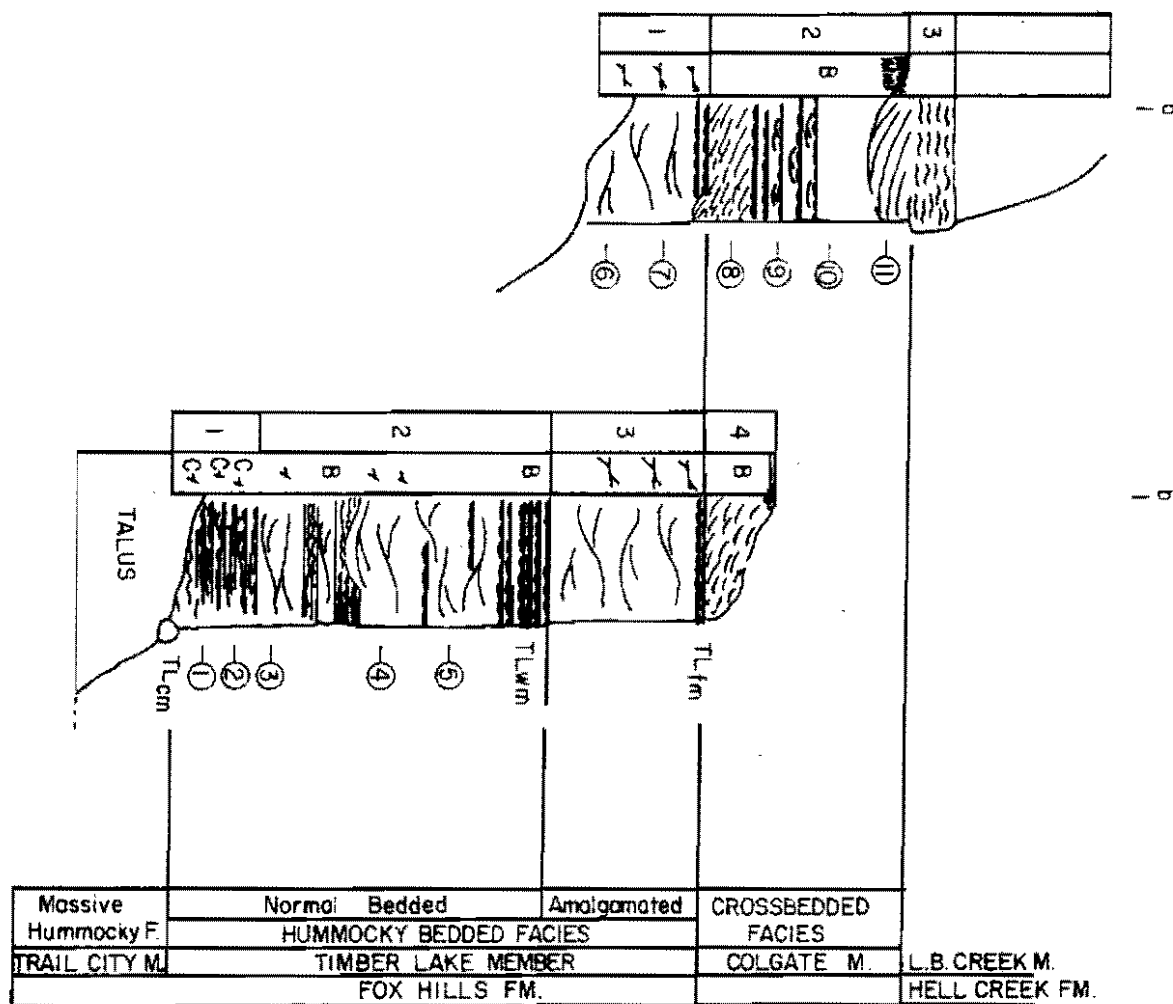
$$\frac{3.0}{21.8}$$

Level of Sevenmile Creek.

Thickness of the Fox Hills Formation
Measured

(24.3)

Figure 75. Measured sections at site 7.



APPENDIX B

SYSTEMATIC PALEONTOLOGY

SYSTEMATIC PALEONTOLOGY

Ichnofossils

Ichnofossils are the preserved indications of behavior and requisite functional morphology that reflect the adaption of organisms to specific environmental conditions (Frey 1978, p. 60).

Trace fossils may be classified in a variety of ways (Simpson 1975): descriptive (non-genetic), preservational (toponomic or stratonomic), behavioral (ethological), and phylogenetic (taxonomic). All ichnological classifications are inherently genetic, since the structures classified were produced biogenetically. The classification adopted here is mainly descriptive-behavioral, supplemented phylogenetically (Frey 1978). The ethological types observed--pascichnia, fodinichnia, and domichnia--are characterized in Figure 76.

Pascichnia

Ichnogenus Cosmorhapse Fuchs 1895

Fig. 77

Synonymy: Hantzschel (1975, p. W53-W55).

Diagnosis.--"Free meanders" of simple, smooth ridges of extraordinarily regular form, meanders commonly of two orders of size; windings not close to each other (Hantzschel 1975, p. W53, pl. 3, fig. 34).

Figure 76. Ethology of trace fossils from the lower
Fox Hills in the study area.

Ethologic Form	Definition	Characteristic Morphology	Representative Fox Hills Form
Domichnia (dwelling)	Burrows or dwelling tubes essentially providing permanent housing, mostly for suspension feeders; emphasis is on habitation.	Simple, bifurcated or U-shaped structures, perpendicular or inclined at various angles to bedding, or branching burrow systems having vertical and horizontal elements; walls typically lined.	<u>Ophiomorpha borneensis</u> <u>Ophiomorpha nodosa</u> forms A, B and C <u>Thalassinoides</u> sp.
Fodinichnia (feeding)	Essentially temporary burrows constructed by deposit feeders; the structure may provide some shelter for the organism; emphasis on feeding, analogous to underground mining.	Single, branched or unbranched, cylindrical to sinuous shafts or U-shaped burrows, or complex, parallel to concentric burrow repetitions (spreiten); walls commonly unlined; oriented at various angles in respect to bedding.	Unidentified forms (study area) <u>Rhizocorallium</u> (Glendive)
Pascichnia (grazing)	Grooves, pits and furrows, many discontinuous, made by mobile deposit feeders at or near the substrate surface; analogous to surface mining.	Unbranched, nonoverlapping, curved to tightly coiled patterns or delicately, constructed spreiten are dominant; patterns reflect maximum utilization of surficial feeding area.	<u>Cosmorhapse</u> sp.

Figure 77. Cosmorhappe. Magnification 2X; grazing trail is 1 mm wide.



Description of material.--Sine-wave-shaped, equiamplitude, continuous groove, confined to the horizontal plane; average wave length 15 mm, amplitude of 7 mm; groove hemispheric, 1 mm wide, 0.5 mm deep.

Occurrence.--This ichnofossil occurred in a 15-cm-thick bioturbated zone at the top of a 0.5-m-thick, indurated hummocky sandy silt bed 5 m above the Pierre-Fox Hills (Trail City Member) contact (site 1c). Ophiomorpha nodosa occurred at the same horizon.

Remarks.--Cosmorhappe represents the grazing trail of a benthonic marine worm and is usually found associated with flysch or turbidite deposits in the record (e. g., Poole 1974, p. 69, fig. 10a; Kern 1978). Cosmorhappe is considered characteristic of the Nerites facies of Sielacher (1967; Chamberlain 1978, fig. 6). Cosmorhappe occurs at the same stratigraphic level with the same sedimentary structures at Fort Peck, Montana, as in the thesis area.

Range.--Ordovician (?) through Holocene.

Domichnia

Ichnogenus Ophiomorpha Lundgren 1891

Fig. 61, 78, 79, 80, 81, 82

Synonymy: Hantzschel (1975, p. W85-W86)



not Spongiomorpha Saporta 1887

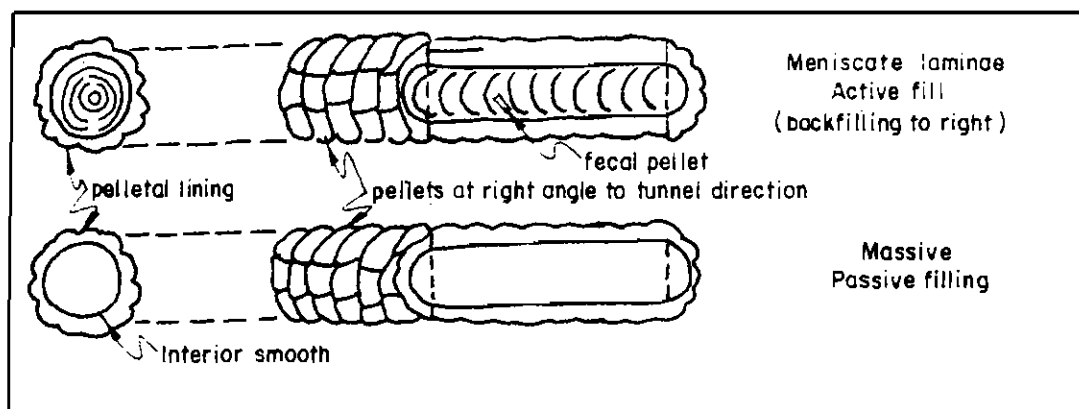
not Ardelia Chamberlain and Baer 1973

Diagnosis.--Simple to complex burrow systems distinctly lined with agglutinated pelletoidal sediment. Burrow lining more or less smooth interiorly; densely to sparsely mammalated or nodose exteriorly.

Figure 78. Species identification in Ophiomorpha based on the pelletal lining (modified from Frey et al. 1978).

Figure 79. The burrow lining and filling for O. borneensis. Many excellent examples of burrows with meniscate filling occur in the upper Timber Lake at site 4.

	BILOBATE PELLETS	<u>O. borneensis</u>
	OVOID PELLETS	<u>O. nodosa</u>



Individual pellets or pelletal masses may be discoid, ovoid, mastoid, bilobate, or irregular in shape. Characteristics of the lining may vary within a single specimen (Frey et al. 1978, p. 222).

Remarks.--Early workers in the Western Interior believed that this material represented a type of seaweed and assigned it to the genus Halymenities. Hantzschel (1952) showed that the form was a trace fossil, probably representing a type of crustacean burrow, and assigned the ichnofossil to the ichnogenus Ophiomorpha.

In a taxonomic scheme based on burrow orientation and lining character, Fursich (1973) included Ophiomorpha and Thalassinoides in the ichnogenus Spongeliomorpha, which had priority. Bromley and Frey (1974) and Frey et al. (1978) considered the character of the burrow lining sufficient to distinguish ichnogenera, and on that basis retained Ophiomorpha as a separate ichnogenus. Within the ichnogenus Ophiomorpha, three ichnospecies are recognized on the basis of variations in the pelletal lining (fig. 78; Frey et al. 1978): O. borneensis, characterized by the presence of bilobate pellets; O. irregulaire, characterized by sparsely distributed ovoid to mastoid pellets; and O. nodosa, characterized by regularly distributed discoid, ovoid, or irregular polygonal pellets.

The ichnofossil Ophiomorpha probably represents the preserved burrows of decapod crustaceans (shrimp) of the superfamily Thalassinoidae, most probably species of Callianassa or Upogebia. Evidence supporting this hypothesis includes: similarities in morphology and pelletal lining between the fossil and modern burrows (Weimer and Hoyt 1964; Smith 1967; Kennedy and MacDougall 1969);

the occurrence, in sediment containing fossil burrows, of fecal pellets and chelae that closely resemble those of Callianassa (Weimer and Hoyt 1964; Pickett et al. 1971; Pryor 1975); and a single reported occurrence of a callianassid chela within a fossil burrow (Waage 1968, pl. 8c).

Range.--Permian to Holocene.

Ichnospecies Ophiomorpha borneensis keij 1965

Fig. 78, 79, 80, 81, 82

Ophiomorpha borneensis Keij 1965; Bromley and Frey 1974, p. 329;

Frey et al. 1978, p. 222, figs. 1B, 4A, 13A, B.

not Spongeliomorpha saxonica (Geinitz) Fursich 1973, p. 729, fig. 6.

Diagnosis.--Burrow walls consist predominantly of dense, regularly distributed, bilobate pellets (Frey et al. 1978).

Description of material.--Exterior burrow diameters are 2.5-4 cm. In cross-section the tunnels consist of an orange-brown, 4-7 mm thick, indurated lining composed of bilobate pellets, and an interior filling composed of loose or indurated sand, massive, or arranged in meniscate laminae (fig. 79). The pellets are lozenge shaped, vary from 3 by 5 mm to 5 by 10 mm, and are usually arranged with their long axis normal to tunnel direction, like bricks in a smokestack (fig. 79). The interior of the lining is smooth.

In the study area, tunnels and galleries are arranged in tiered mazes 0.3-0.6 m thick (fig. 82; Frey et al. 1978, fig. 2F); horizontal components (galleries) are abundant but vertical elements

Figure 80. Plan view of an O. borneensis gallery layer. The curved tunnel may have been constructed by an adult male with an enlarged chela.

Figure 81. O. borneensis "wagon wheel". The tape is 1 m. Photo from site 7a.

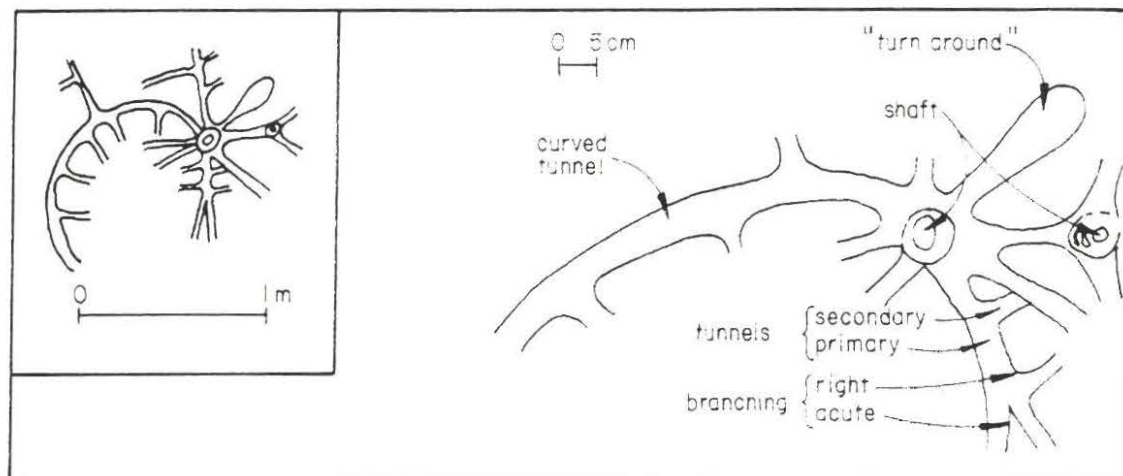


Figure 82. Tiered mazes of O. borneensis. Three maze layers are visible above the pick head. The pick is 0.6 m. Photo from site 2-2.

Figure 83. Thalassinoides (?). Only a single example of this dwelling trace was found in the study area. Scale is 15 cm. Photo from site 5a.



(shafts) are rare. Vertical elements connect maze tiers; remnant shafts, 2-3 cm in height, occur atop maze systems. In the horizontal plane, the tiers, composed of tunnels radiating from shafts, are often circular, giving the appearance of rimless wagon wheels; each "wheel" covered 1-4 m² (fig. 80, 81).

The tunnels branch at Y or T junctions. Diameters typically remained constant across junctions, but smaller diameter tunnels were seen to branch from large diameter main tunnels. Enlarged tunnel portions, "turn-arounds", occur at joints and dead-ends.

Occurrence.--O. borneensis occurs most abundantly in the moderately sorted, fine sand of the upper Timber Lake Member (amalgamated subfacies of the hummocky bedded facies) where they occur in 2-3 m thick bioturbation zones. The zones may contain tiered galleries (sites 5a, 6c, 7a) or densely packed remains (sites 4, 6d).

In the Colgate Member, O. borneensis remains are rare. At site 6d, a 2-m-thick zone of densely packed tunnels occurred at the base of the member; at site 4 burrows were rare and isolated, characterized by a poorly indurated gray clay pelletal lining, and were associated with trough cross-bedding.

The Colgate-Timber Lake contact typically coincides with the highest occurrence of O. borneensis.

Remarks.--No crustacean body fossils were associated with these burrows. Gray clay rods, 1 by 3 mm, were found concentrated along hummocky laminae and within burrows containing meniscate laminae. These rods are similar in size and shape to the fecal pellets of

Callianassa major (Weimer and Hoyt 1964; Pryor 1975). Brown (1939, pl. 62, fig. 6, 7) collected tunnel specimens from the Little Beaver Creek outcrops that were filled with these fecal pellets.

The presence of meniscate laminae in the burrow indicates active filling by the crustacean (Chamberlain 1978; fig. 79) and results from the filling-in of older tunnels with freshly excavated material (Pohl 1946; Hill and Hunter 1972).

Fursich (1973, p. 724) noted that the preferential preservation of horizontal elements in a burrow system could be the result of: (1) the destruction of vertical elements originally present in the system; (2) burrowing in a shallow sand substrate; (3) or burrowing in a low energy environment. The latter two possibilities represent conditions in which vertical elements are not produced by the burrowing organism. The thickness of the substrate and the presence of some vertical elements indicates that shafts were originally present.

I suggest that the apparent lack of vertical components is an artifact of low observation incidence (due to the predominance of vertical outcrop faces) coupled with a lack of preservation. Lack of preservation could be the result of: (1) erosion and re-deposition in the horizontal plane (Warne and Stanton 1971); (2) penecontemporaneous destruction; or (3) erosion from the outcrop. Individual lining pellets were found concentrated along hummocky laminae indicating some penecontemporaneous destruction. Remnant shafts stop horizontal gallery systems and weathered vertical elements indicate more recent destruction. No evidence was found for the redeposition of vertical elements in the horizontal plane.

The limited preservation of some vertical elements indicates that the burrow systems were three-dimensional with gallery systems occurring at least 0.5 m below the substrate surface as evidenced by the preservation of probable surface-connecting shafts.

Outside the study area, Ophiomorpha borneensis occurs in the upper portion of the Timber Lake Member at Glendive, but I have not observed it in other areas. Waage's (1968, pl. 8c) specimen, as well as the large form described by Klett and Erickson (1976) from the Linton Member, may be O. borneensis.

Interpretation.--Burrow systems were constructed by a species of decapod crustacean similar in size and habit to C. major as evidenced by similarities in fecal pellets and overall burrow morphology, including diameter and geometry. In this case, the horizontal gallery system has been preferentially preserved through the combination of penecontemporaneous and recent destruction of vertical elements. The substrate surface probably occurred at least 0.5 m above the level of the gallery.

Ichnospecies Ophiomorpha nodosa Lundgren 1891

Ophiomorpha nodosa Lundgren: (for synonymy) Kennedy and MacDougall 1969; Frey et al. 1978.

Diagnosis.--Burrow walls consist predominantly of dense, regularly disturbed discoid, ovoid, or irregular polygonal pellets (Frey et al. 1978).

Description of material.--Three informal forms--A, B and C--were differentiated on the basis of burrow diameter. The burrows of

form A have an external diameter of 5-7 mm and a pelletal lining 1 mm thick that is composed of 1 mm diameter pellets. The burrows of form B have external diameters of 1.5-2 cm, a pelletal lining 3 mm thick and pellets 3-4 mm in diameter. Both forms A and B occur in irregular boxworks (Frey et al. 1978, fig. 2E) 10-20 cm thick. Form C is characterized by vertical shafts 1-2 mm in diameter and 2-3 cm long that occur in groups.

Occurrence.--Forms A and B occur together in the hummocky beds of the Trail City Member (with Cosmorhapha at site 1c) and in the normal-bedded subfacies of the lower Timber Lake Member especially at sites 2b, 2d, 5a and 7b. These forms occur in the upper Timber Lake at site 2b. These forms occur in zones at the top of hummocky beds (diffuse bases and sharp, erosional tops) but may occur as isolated individuals (site 5a).

Form C was observed only at site 7b where it occurred at the base of the Timber Lake Member with forms A and B in hummocky bedding. The form occupied the very tops of the hummocky beds.

Remarks.--No fecal pellets or body fossils of crustaceans were found in association with Ophiomorpha nodosa. Often, the burrow linings were not indurated, but were composed of gray or rust-colored clay or silty clay. External molds of the burrows are plentiful in the hummock-form concretions of the lower Timber Lake. No complete burrow systems were observed probably due to destruction at the outcrop.

Forms A, B and C occur in the upper Timber Lake Member (in trough cross-bedding) at the mouth of the Cannonball River (site 7-2)

in Sioux County, North Dakota. Forms A and B occur in the lower Timber Lake at Fort Peck, Montana (Site I-1) and in the lower Fairpoint Member in Meade County, South Dakota (site 4-1).

Interpretation.--The burrows were probably constructed by decapod crustaceans similar in size and habit to the modern Callianassa biformis or Callianassa atlanticus (fig. 61).

Differences between the three forms--A, B and C--could be a reflection of different burrowing species or the maturity (size) of the burrowing organism. Forms A and C might represent juveniles of form B.

Thalassinoides (?) sp.

fig. 83

Description of material.--Vertical cylinder 2.5 cm in diameter at top, 24 cm high, with diameter swelling gradually downward to a 5 cm diameter over the basal 6 cm; capped by an incomplete horizontal, cylindrical crosspiece 1.5 cm diameter, 3 cm long; smooth exterior lining.

Occurrence.--A single incomplete example of this form occurred in a massive sandy-silt concretion of the TLcm (site 5a).

Remarks.--This specimen represents a remnant of a larger burrow system. On the basis of the smooth lining and the presence of horizontal and vertical elements the specimen is assigned to the ichnogenus Thalassinoides (Hantzschel 1978; Chamberlain 1978, p. 136, figs. 63-64, 89, Chart 1). Little could be learned of the character of the lining or the internal filling due to the fine grain size. This trace is formed by burrowing crustaceans and has been reported

to be a non-pelletal version of Ophiomorpha in fine sediment (Frey et al. 1978; Fursich 1973; Kennedy and MacDougall 1969). No evidence for such an explanation was found in association with this specimen.

Fossil Flora

(Spermatophyta (?))

Fagaceae (?)

Dryophyllum sp. (?)

Description of material.--Leaves lanceolate with pinneate venation and entire margins; 11 cm long, 2 cm wide; form incomplete.

Occurrence.--Leaf impressions occurred in a leaf-rich hash zone just below the Colgate-Hell Creek contact at site 1b on Little Beaver Creek.

Remarks.--This form most closely resembles D. subfalcatum Lesquereux (Brown 1939, p. 248, pl. 50, fig. 1-8; pl. 51, figs. 1-7; pl. 52, figs. 1-3; pl. 54, fig. 1), a species common in the Colgate Member. Incomplete examples of this form preclude positive identification.

Equisetum (?)

Description of material.--Parallel venation; grass-like; 2 cm wide; fossils incomplete.

Occurrence.--Equisetum occurred in a zone just below the Colgate-Hell Creek contact at sites 1b on Little Beaver Creek, 2c at North Creek and 6d at Horse Creek.

Remarks.--The form closely resembled Equisetum (horsetail; Brown 1939; p. 248; pl. 61, fig. 14). Incomplete examples of the form preclude positive identification.

Root Molds

Description of material.--Vertical, occasionally bifurcated, carbonized molds; 0.3-1 m long and 2 mm wide.

Occurrence.--Root molds occurred in a zone up to 2 m thick just below the Hell Creek-Colgate contact at North Creek (site 2), at Sevenmile Creek (site 7a) and in the Horse Creek exposures (sites 6b, 6d, 6f). Roots were not observed at the S-curve exposures (site 4) or at Little Beaver Creek (site 1) where large scale cross-bedding occurred in the Colgate.

Remarks.--Lamination was not present in the sediment of the root mold zone. The root molds were similar to those reported from the Linton Member (Klett and Erickson, 1976). The roots do not resemble the tree roots in the Colgate at Crowghost Cemetery (site 7-1; Carlson 1979). No taxonomic interpretation was possible from these traces.

APPENDIX C
SAND TEXTURAL DATA

Sand Textural Data

For each sample analyzed, Appendix C provides: the percentage of sand; the 50th, 16th, and 84th grain size percentiles in phi units (ϕ); and the sorting values (well = W; moderate = M; poor = P). Although 99 samples were collected, only 74 were analyzed. The remainder were discarded because they contained large amounts of carbonaceous material, were bioturbated, or contained part of a wavy layer. The procedures for sampling and preparation are described under Methods (p. 46-47).

On the following pages, the sampled sites--1, 4, and 7--are given at the bottom of the page. The sample horizon (10, for example) and the sample along the horizon (A, B, or C) are listed on the left-hand side. The data are further arranged by sedimentary structure facies or subfacies--8-11 indicate cross-bedded facies, 5-7 indicate amalgamated subfacies, and 1-4 indicate normal bedded subfacies. For site 1: horizon 1 was collected from a hummocky lenticle; sample 2 from a ripple layer; and 3 and 4 from the hummocky bedding. The crossbedded strata at site 4 represent channel deposits; those at 1 and 7 represent shoreface deposits. The data from horizons 1-7 represent the Timber Lake Member; the data from 8-11 represent the Colgate Member.

Sampling Horizon	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing
A	83	3.1	2.75	4.2	M	68	2.85	2.45	--	P	--	--	--	--	--
11 B	84	2.88	2.5	4.2	M	74	2.75	2.4	--	P	--	--	--	--	--
C	--	--	--	--	--	73	2.80	2.4	--	P	--	--	--	--	--
A	--	--	--	--	--	76	3.3	2.85	5.0	P	77	3.1	2.8	5.0	P
10 B	84	2.67	2.33	3.85	M	--	--	--	--	--	85	2.68	2.35	3.95	M
C	83	2.75	2.4	4.5	M	81	3.15	2.8	4.25	P	--	--	--	--	--
A	76	3.3	2.85	5.0	M	69	2.5	2.0	--	P	--	--	--	--	--
9 B	72	3.25	2.9	--	P	88	3.25	1.95	3.4	M	80	3.25	2.75	5.0	M
C	73	3.25	2.8	--	P	74	2.6	2.05	--	P	80	3.0	2.6	5.0	P
A	--	--	--	--	--	85	2.8	2.45	3.95	M	77	3.07	2.75	--	P
8 B	--	--	--	--	--	79	2.95	2.4	4.5	M	83	3.1	2.8	4.25	M
C	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Site 1

Site 4

Site 7

Sampling Horizon	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing
A	84	3.05	2.7	4.0	MW	85	3.07	2.6	3.95	MW	86	3.18	2.95	3.7	W
7 B	82	2.92	2.65	4.5	M	85	3.0	2.65	3.95	MW	87.5	3.12	2.85	3.45	W
C	85	3.1	2.7	3.95	MW	84	3.1	2.55	4.0	MW	83	3.15	2.9	4.0	MW
A	--	--	--	--	--	90	2.95	2.6	3.25	--	81	2.9	2.8	4.5	M
6 B	--	--	--	--	--	81	3.1	2.85	4.5	M	82	3.0	2.85	4.5	M
C	85	3.1	2.7	3.95	MW	80	3.3	2.9	4.5	M	79	3.24	3.05	5.0	M
A	80	3.25	3.5	4.5	MW	82	3.25	3.0	4.5	M	--	--	--	--	--
5 B	83	3.25	3.55	5.0	M	83	3.25	3.0	4.5	M	--	--	--	--	--
C	--	--	--	--	--	80	3.3	3.05	5.0	M	--	--	--	--	--

Site 1

Site 4

Site 7

Sample Horizon	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing	% Sand	Ø 50	Ø 16	Ø 84	Sort- ing
A	71	3.55	3.3	5.0	M	--	--	--	--	--	60	3.8	3.4	4.7	M
4 B	70	3.5	3.2	5.0	M	75	3.6	3.4	4.5	M	65	3.6	3.4	4.5	M
C	71	3.45	3.2	--	P	67	3.65	3.35	5.0	M	--	--	--	--	--
A	68	3.7	3.35	4.5	M	64	3.65	3.4	--	--	51	3.85	3.35	4.8	M
3 B	69	3.7	3.35	4.5	M	59	3.65	3.35	--	--	--	--	--	--	--
C	69	3.7	3.4	5.0	M	61	3.85	3.5	--	--	46	4.2	3.5	--	--
A	24	--	3.8	--	--	51	3.95	3.65	--	--	60	3.9	3.5	--	P
2 B	36	--	3.65	--	--	26	--	3.8	--	--	25	--	3.9	--	--
C	33	--	3.8	--	--	27	--	3.85	--	--	40	4.1	3.7	--	--
A	57	3.85	3.4	--	--	--	--	--	--	--	20	--	3.9	--	--
1 B	52	3.95	3.6	--	--	--	--	--	--	--	20	--	3.85	--	--
C	49	4.1	3.6	--	--	18	--	3.95	--	--	--	--	--	--	--

Site 1

Site 4

Site 7

REFERENCES

References

- Allen, J. R. L., 1963, The classification of cross stratified units with notes on their origin: *Sedimentology*, v. 2, p. 93-114.
- Allen, J. R. L., 1982, Chapter 12, Storm sequences in shallow water, in *Developments in sedimentology*, 30B, *Sedimentary structures: Their character and physical basis*, Volume II: New York, Elsevier, p. 471-506.
- Asquith, D. O., 1970, Depositional topography and major marine environments, Late Cretaceous, Wyoming: *Bulletin of the American Association of Petroleum Geologists*, v. 54, p. 1184-1224.
- Bergantino, R. N., 1980, Geologic map of the Ekalaka 1 x 2 quadrangle, southeastern Montana: Montana Atlas 1-A, Montana Bureau of Mines and Geology.
- Bishop, G. A., 1973, Geology, stratigraphy, and biostratigraphy of the north end of Cedar Creek Anticline, Dawson County, Montana: Montana Bureau of Mines and Geology Special Publication, 61, 2 p.
- Bluemle, J. P., Anderson, S. B., and Carlson, C. G., 1981, Williston Basin stratigraphic nomenclature chart: North Dakota Geological Survey, Miscellaneous Series no. 61.
- Boersma, J. R., 1970, Distinguishing features of wave-ripple cross-stratification and morphology: Doctoral thesis, University of Utrecht, 65 p.
- Bourgeois, J., 1980, A transgressive shelf sequence exhibiting hummocky stratification: The Cape Sebastian Sandstone (Upper Cretaceous), southwestern Oregon: *Journal of Sedimentary Petrology*, v. 50, p. 681-702.
- Bretz, G. K., 1983, South Dakota Geological Survey, Rapid City, South Dakota, verbal communication.
- Bromley, R. G., and Frey, R. W., 1974, Redescription of the trace fossil Gyrolithes and taxonomic evaluation of Thalassinoides, Ophiomorpha, and Spongeliomorpha: *Geological Society of Denmark Bulletin*, v. 23, p. 311-335.

- Brown, R. W., 1939, Fossil plants from the Colgate Member of the Fox Hills Sandstone and adjacent strata: United States Geological Survey Professional Paper 189-I, p. 239-275.
- Brown, R. W., 1962, Paleocene flora of the Rocky Mountains and Great Plains: United States Geological Survey Professional Paper 375, 119 p.
- Butler, R. D., 1980, Stratigraphy, sedimentology, and depositional environments of the Hell Creek Formation (Late Cretaceous) and adjacent strata, Glendive area, Montana: Ph.D. dissertation, University of North Dakota, 398 p.
- Carlson, C. G., 1979, Geology of Adams and Bowman Counties, North Dakota: North Dakota Geological Survey Bulletin 65, Pt. 1, 29 p.
- Carlson, C. G., 1982, Geology of Grant and Sioux Counties, North Dakota: North Dakota Geological Survey Bulletin 67, 32 p.
- Carlson, C. G., and Anderson, S. B., 1970, Sedimentary and tectonic history of North Dakota part of Williston Basin: North Dakota Geological Survey Miscellaneous Series no. 28, 14 p.
- Calvert, W. R., 1912, Geology of certain lignite fields in eastern Montana: United States Geological Survey Bulletin 471, p. 182-201.
- Calvert, W. R., Beekley, A. L., Barnett, V. H., and Pishel, M. A., 1914, Geology of the Standing Rock and Cheyenne River Indian Reservations, North and South Dakota: United States Geological Survey Bulletin, 49 p.
- Campbell, C. V., 1966, Truncated wave-ripple laminae: Journal of Sedimentary Petrology, v. 36, p. 825-828.
- Carver, R. E., ed., 1971, Procedures in sedimentary petrology: New York, Wiley-Interscience, 653 p.
- Chamberlain, C. K., 1978, Chapter 5, Recognition of trace fossils in cores, in Basan, P. B., ed., Trace fossil concepts: Oklahoma City, Oklahoma, Society of Economic Paleontologists and Mineralogists Short Course no. 5, p. 119-166.
- Clement, J. H., 1983, Shell Oil Company, Houston, Texas, written communication.

- Clifton, H. E., 1976, Wave-formed sedimentary structures: A conceptual model, in Davis, R. A., Jr., and Ethington, R. L., eds., Beach and nearshore sedimentation: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication no. 24, p. 126-148.
- Clifton, H. E., Hunter, H. E., and Phillips, R. L., 1971, Depositional structures and processes in the non-barred high energy nearshore: Journal of Sedimentary Petrology, v. 41, p. 651-670.
- Cobban, W. A., and Reeside, J. B., Jr., 1952, Correlation of the Cretaceous formations of the western interior of the United States: Geological Society of America Bulletin, v. 63, p. 1011-1044.
- Collier, A. J., and Knechtel, M. M., 1939, The coal resources of McCone County, Montana: United States Geological Survey Bulletin 905.
- Curtiss, R. E., 1952, Aerial geology of the Isabel quadrangle: South Dakota Geological Survey Geological Quadrangle, 1 p.
- Cvancara, A. M., 1976, Geology of the Fox Hills Formation (Late Cretaceous) in the Williston Basin of North Dakota, with reference to uranium potential: North Dakota Geological Survey Report of Investigations no. 55, 16 p.
- Davidson-Arnott, R. G., and Greenwood, B., 1976, Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick, Canada, in Davis, R. A., Jr., and Ethington, R. L., eds., Beach and nearshore sedimentation: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication no. 24, p. 149-168.
- Davis, J. R., 1966, Stratigraphy and deposition history of upper "Mesa Verde" Formation of southeastern Wyoming: Ph.D. dissertation, University of Wyoming, 428 p.
- Devine, C. E., 1966, Ecology of Callianassa filholi Milne-Edwards 1878 (Crustacea, Thalassinidea): Transactions of the Royal Society of New Zealand, v. 8, p. 93-110.
- Dobbin, C. E., and Larsen, R. M., 1966, Geologic and structure contour map of the southern half of the Cedar Creek anticline, Fallon County, Montana, and Bowman County, North Dakota: United States Geological Survey.

- Dobbin, C. E., and Reeside, J. B., 1929, The contact of the Fox Hills and Lance Formations: United States Geological Survey Professional Paper 158, p. 9-25.
- Dorf, E., 1942, Upper Cretaceous floras of the Rocky Mountain Region: Carnegie Institution of Washington Publication 508, p. 1-78.
- Dott, R. H., Jr., 1983, Episodic sedimentation--How normal is average? How rare is rare? Does it matter?: Journal of Sedimentary Petrology, v. 53, p. 5-23.
- Dott, R. H., Jr., and Batten, R. L., 1971, Evolution of the earth: New York, McGraw-Hill Book Company, 649 p.
- Dott, R. H., Jr., and Bourgeois, J., 1982, Hummocky stratification: Significance of its variable bedding sequences: Geological Society of America Bulletin, v. 93, no. 8, 663-680.
- Drake, D. E., Kolpack, R. L., and Fischer, P. J., 1972, Sediment transport on the Santa Barbara-Oxnard Shelf, Santa Barbara Channel, California: in Swift, D. J. P., Duane, D. B., and Pilkey, O. H., eds., Shelf sediment transport: process and pattern: Shroudsburg, Pa., Dowden, Hutchinson and Ross, p. 307-331.
- Elridge, G. H., 1889, Some suggestions upon the methods of grouping the formation of the middle Cretaceous and the employment of an additional term in its nomenclature: American Journal of Science, v. 38, 313-321.
- Erdmann, C. E., and Larsen, R. M., 1934, Geologic and structure contour map of the northern half of the Cedar Creek anticline, Dawson, Prairie, Wibaux, Fallon Counties, Montana: United States Geological Survey.
- Erickson, J. M., 1971, Gastropoda of the Fox Hills Formation (Maestrichtian) of North Dakota: Ph.D. dissertation, University of North Dakota 247 p.
- Erickson, J. M., 1974, Revision of the Gastropoda of the Fox Hills Formation, Upper Cretaceous (Maestrichtian) of North Dakota: Bulletin of American Paleontologists, v. 66, p. 127-253.
- Feldmann, R. M., 1967, Bivalvia and paleoecology of the Fox Hills Formation (Upper Cretaceous) of North Dakota: Ph.D. dissertation, University of North Dakota, 365 p.

- Feldmann, R. D., 1972, Stratigraphy and paleoecology of the Fox Hills Formation (Upper Cretaceous) of North Dakota: North Dakota Geological Survey Bulletin 61, 65 p.
- Fisher, S. P., 1952, The geology of Emmons County, North Dakota: North Dakota Geological Survey Bulletin 26, 47 p.
- Folk, R. L., 1965, Petrology of sedimentary rocks: Hemphill's 159 p.
- Frey, R. W., 1978, Behavioral and ecological implications of trace fossils: in Basan, P. B., ed., Trace fossil concepts: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Short Course no. 5, p. 43-66.
- Frey, R. W., and Howard, J. D., 1969, A profile of biogenic sedimentary structures in a Holocene barrier island-salt marsh complex, Georgia: Transactions of the Gulf Coast Association of Geological Societies, v. 19, p. 427-444.
- Frey, R. W., Howard, J. D., and Pryor, W. A., 1978, Ophiomorpha: Its morphologic, taxonomic, and environmental significance: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 23, p. 199-229.
- Frey, R. W., and Mayou, T. V., 1971, Decapod burrows in Holocene barrier island beaches and washover fans, Georgia: Senckenbergiana Maritima, v. 3, p. 53-77.
- Frye, C. I., 1967, The Hell Creek Formation in North Dakota: Ph.D. dissertation, University of North Dakota, 411 p.
- Frye, C. I., 1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geological Survey Bulletin 54, 65 p.
- Fursich, F. T., 1973, A revision of the trace fossils Spongiomorpha, Ophiomorpha and Thalassinoides: Neues Jahrbuch für Geologie und Paläontologie, Monatshefte 1973, p. 719-735.
- Gadow, S., and Reineck, H. E., 1969, Ablandiger Sandtransport bei Sturmfluten: Senckenbergiana Maritima, v. 1, p. 63-78.
- Gerhard, L. C., Anderson, S. B., LeFever, J. A., and Carlson, C. G., 1982, Geological development, origin, and energy and mineral resources of the Williston Basin, North Dakota: Bulletin of the American Association of Petroleum Geologists, v. 66, p. 989-1020.

- Gill, J. R., and Cobban, W. A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming and North and South Dakota: United States Geological Survey Professional Paper 776, 37 p.
- Goddard, E. N., Trask, P. D., DeFord, R. K., Rove, O. N., Stingwald, J. T., Jr., and Overbeck, R. M., 1963, Rock-color chart: New York Geological Society of America.
- Groenewold, G. H., Hemish, L. A., Cherry, J. A., Rehm, B. W., Meyer, G. N., and Winczewski, L. M., 1979, Geology and geohydrology of the Knife River Basin and adjacent areas of west-central North Dakota: North Dakota Geological Survey, Report of Investigation no. 64, 402 p.
- Hamblin, A. P., Duke, W. L., and Walker, R. G., 1979, Hummocky cross-stratification--Indicator of storm dominated shallow-marine environments, abs.: Bulletin of the American Association of Petroleum Geologists, v. 63, p. 460-461.
- Hantzschel, W., 1952, Die Lebenspur Ophiomorpha Lundgren in Miozan bei Hamburg ihre weltweite Verbreitung und Synonymie: Mitteilungen geologisches Staat-Institute Hamburg, v. 21, p. 142-153.
- Hantzschel, W., 1975, Trace fossils and problematica 22nd edition: Treatise on invertebrate paleontology, Pt. W. Miscellaneous Supplement 1, Teichert, C., ed., Geological Society of America and University of Kansas, Boulder, Colorado, and Lawrence, Kansas, 269 p.
- Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: United States Geological Survey Bulletin, 775, 110 p.
- Harms, J. C., and Fahnestock, R. K., 1965, Stratification, bedforms, and flow phenomena (with an example from the Rio Grande): in Society of Economic Paleontologists and Mineralogists Special Publication 12, p. 84-115.
- Harms, J. C., MacKenzie, D. B., and McCubbin, D. G., 1965, Depositional environment of the Fox Hills Sandstones near Rock Springs, Wyoming: Wyoming Geological Association Guidebook, 19th Annual Field Conference, p. 113-130.
- Harms, J. C., Southard, J. B., Spearing, D. R., and Walker, R. G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Short Course no. 2, p. 161.
- Harms, J. C., Southard, J. B., and Walker, R. G., 1982, Structures and sequences in clastic rocks: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Short Course no. 9, 249 p.

- Hawley, N., 1981, Flume experiments on the origin of flaser bedding: *Sedimentology*, v. 28, p. 699-712.
- Hertweck, G., 1972, Georgia coastal region, Sapelo Island, U. S. A.: V. Distribution and environmental significance of lebenspuren and in-situ skeletal remains: *Senckenbergiana Maritima*, v. 4, p. 125-167.
- Hill, G. W., and Hunter, R. E., 1976, Interaction of biological and geological processes in the beach and nearshore, northern Padre Island, Texas in Davis, R. A., Jr., and Ethington, R. L., eds., *Beach and nearshore sedimentation*: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication no. 24, p. 169-187.
- Homziak, J., 1981, Resource partitioning among three species of Callianassid shrimps, abs.: *American Zoologist*, v. 21, p. 943.
- Howard, J. D., 1972, Trace fossils as criteria for recognizing shorelines in the stratigraphic record, in *Recognition of ancient sedimentary environments*, Rigby, J. K., and Hamblin, W. K., eds., Society of Economic Paleontologists and Mineralogists Special Publication no. 16, p. 215-225.
- Howard, J. D., 1978, Chapter 2, Sedimentology and trace fossils, in Basan, P. B., ed., *Trace fossil concepts*: Oklahoma City, Society of Economic Paleontologists and Mineralogists Short course no. 5, p. 11-44.
- Howard, J. D., and Frey, R. W., 1975, Estuaries of the Georgia coast, U. S. A.: sedimentology and biology. II. Regional animal-sediment characteristics of Georgia estuaries: *Senckenbergiana Maritima*, v. 7, p. 33-103.
- Howard, J. D., and Reineck, H. E., 1981, Depositional facies of high energy beach to offshore sequence: comparison with low energy sequence: *Bulletin of the American Association of Petroleum Geologists*, v. 65, p. 807-830.
- Hoyt, J. H., and Henry, V. J., 1967, Influence of island migration on barrier-island sedimentation: *Geological Survey of America Bulletin*, v. 78, p. 77-86.
- Jeletzky, J. A., 1962, The alledgedly Danian dinosaur-bearing rocks of the globe and the problem of the Mesozoic-Cenozoic boundary: *Journal of Paleontology*, v. 36, p. 1005-1018.
- Jensen, F. S., 1951, Disconformity at the contact of the Fox Hills Sandstone and Hell Creek Formation in northeastern Montana, abs.: *Geological Society of America Bulletin*, v. 62, p. 1453.

- Jensen, F. S., and Varnes, H. D., 1964, Geology of the Fork Peck area, Garfield, McCone and Valley Counties, Montana: United States Geological Survey Professional Paper 414-F, p. 1-49.
- Jopling, A. V., 1965, Hydraulic factors controlling the shape of laminae in laboratory deltas: *Journal of Sedimentary Petrology*, v. 35, p. 777-791.
- Kennedy, W. J., and MacDougall, J. D. S., 1969, Crustacean burrows in the Weald Clay (Lower Cretaceous) of south-eastern England and their environmental significance: *Palaeontology*, v. 12, p. 459-471.
- Kern, J. P., 1978, Trails from the Vienna Woods: paleoenvironments and trace fossils of Cretaceous to Eocene flysch, Vienna, Austria: *Paleogeography, Paleoclimatology, Paleoecology*, v. 23, p. 231-262.
- Kern, J. P., and Warne, J. E., 1974, Trace fossils and bathymetry of the Upper Cretaceous Point Loma Formation, San Diego, California: *Geological Society of America Bulletin*, v. 85, p. 893-900.
- Klein, G. deV., 1974, Estimating water depths from analysis of barrier island and deltaic sedimentary sequences: *Geology*, v. 2, p. 409-412.
- Klett, M. C. and Erickson, J. M., 1976, Type and reference sections for a new member of the Fox Hills Formation, Upper Cretaceous (Maestrichtian) in the Missouri Valley region, North and South Dakota: *Proceedings of the North Dakota Academy of Science*, v. 28, pt. II.
- Kreisa, R. D., 1980, Storm-generated sedimentary structures in subtidal marine facies with examples from the middle and upper Ordovician of southwestern Virginia: *Journal of Sedimentary Petrology*, v. 51, p. 823-848.
- Kulm, L. D., Roush, R. C., Harlett, J. C., Neudeck, R. H., Chambers, D. M., and Runge, E. J., 1975, Oregon continental shelf sedimentation: Interrelationships of facies distribution and sedimentary processes: *Journal of Geology*, v. 83, p. 145-175.
- Laird, W. M., and Mitchell, R. H., 1942, The geology of the southern part of Morton County, North Dakota: *North Dakota Geological Survey Bulletin* 14, 42 p.

- Land, C. B., 1972, Stratigraphy of the Fox Hills Sandstone and associated formations, Rock Springs Uplift and Wamsutter Arch area, Sweetwater County, Wyoming: A shoreline estuary sandstone model for the late Cretaceous: Quarterly of the Colorado School of Mines, v. 67, 69 p.
- Leonard, A. G., 1906, The North Dakota-Montana lignite area: United States Geological Survey Bulletin, v. 285, p. 316-330.
- Leonard, A. G., 1908, The geology of southwestern North Dakota with special reference to the coal: North Dakota Geological Survey Fifth Biennial Report, p. 27-114.
- Leonard, A. G., 1911, The Cretaceous and Tertiary formations of western North Dakota and eastern Montana: Journal of Geology, v. 19, p. 507-547.
- Leonard, A. G., 1912, The geology of south central North Dakota: North Dakota Geological Survey Sixth Biennial Report, p. 21-99.
- Lovering, T. S., Aurand, H. A., Larrington, C. S., and Wilson, J. H., 1932, Fox Hills Formation, northeastern Colorado: Bulletin of the American Association of Petroleum Geologists, v. 16, p. 702-3.
- MacGinitie, G. E., and MacGinitie, N., 1949, Natural history of marine animals: New York, McGraw Book Company, Inc., p. 284-293.
- Masters, C. D., 1967, Use of sedimentary structures in determination of depositional environments, Mesaverde Formation, Williams Fork Mountains, Colorado: Bulletin of the American Association of Petroleum Geologists, v. 51, p. 2033-2043.
- McGookey, D. P., Haun, J. D., Hale, L. A., Godell, H. G., McCubbin, D. G., Weimer, R. J., and Wulf, G. R., 1972, Cretaceous system, in Rocky Mountain Association of Geologists, Geologic Atlas of the Rocky Mountain Region: Denver, Rocky Mountain Association of Geologists, p. 190-228.
- Morgan, R. E., and Petsch, B. C., 1945, A geological survey in Dewey and Corson Counties, South Dakota: South Dakota Geological Survey Report of Investigations 49, 45 p.
- Neef, G., 1978, Ophiomorpha ichnofossils from Late Miocene sandstone near Little Wanganui settlement, Buller, South Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 21, p. 419-421.

- Osgood, R. G., and Szmuc, E. J., 1972, The trace fossil Zoophycus as an indicator of water depth: Bulletin of American Paleontology, v. 62, p. 1-22.
- Otto, G. H., 1938, The sedimentation unit and its use in field sampling: Journal of Geology, v. 46, p. 569-582.
- Pettyjohn, W. A., 1967, New members of the Upper Cretaceous Fox Hills Formation in South Dakota representing delta deposits: Bulletin of the American Association of Petroleum Geologists, v. 51, p. 1361-1367.
- Pettyjohn, F. J., and Potter, P. E., 1964, Atlas and glossary of primary sedimentary structures: New York, Springer-Verlag, 370 p.
- Pickett, T. E., Kraft, J. C., and Smith, K. L., 1971, Cretaceous burrows--Chesapeake and Delaware Canal, Delaware: Journal of Paleontology, v. 45, p. 209-211.
- Pohl, M. E., 1946, Ecological observations on Callianassa major Say at Beaufort, North Carolina: Ecology, v. 27, p. 71-90.
- Poole, F. G., 1974, Flysch deposits of the Antler foreland basin, western United States: in Dickinson, W. R., ed., Tectonics and sedimentation: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists Special Publication no. 22, p. 58-82.
- Pryor, W. A., 1975, Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments: Geological Society of American Bulletin, v. 86, 1244-1254.
- Reddering, J. S. V., 1983, An inlet sequence produced by migration of a small microtidal inlet against longshore drift: the Keurbooms Inlet, South Africa: Sedimentology, v. 30, 201-218.
- Reineck, H. E., and Singh, I. B., 1971, Der Golf von Gaeta (Tyrrhenisches Meer): Senckenbergiana Maritima, v. 3, p. 185-201.
- Reineck, H. E., and Singh, I. B., 1972, Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud: Sedimentology, v. 18, p. 123-128.
- Reineck, H. E., and Singh, I. B., 1975, Depositional Sedimentary Environments: New York, Springer-Verlag, 439 p.
- Searight, W. V., 1934, The Stoneville Coal Area: South Dakota Geological Survey Report of Investigation 22, 20 p.
- Seilacher, A., 1967, Bathymetry of trace fossils: Marine Geology, v. 5, p. 413-429.

- Simpson, S., 1975, Classification of trace fossils: in Frey, R. W., ed., The study of trace fossils: Springer-Verlag, New York, p. 39-54.
- Smith, J. D., and Hopkins, T. S., 1972, Sediment transport on the continental shelf off Washington and Oregon in light of recent current measurements: in Swift, D. J. P., Duane, D. B., and Pilkey, O. H., eds., Shelf sediment transport: process and pattern: Shroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, p. 143-180.
- Smith, K. L., Jr., 1967, Callianassid crustacean burrows as possible paleoenvironmental indicators: M.S. thesis, University of Delaware, Newark, Delaware, 63 p.
- Speden, I. G., 1970, The type Fox Hills Formation, Cretaceous (Maestrichtian), Part 2. Systematics of the Bivalvia: Peabody Museum of Natural History (Yale University) Bulletin 33, 222 p.
- Stanton, T. W., 1910, Fox Hills Sandstone and Lance Formation ("Ceratops Beds") in South Dakota, North Dakota and eastern Wyoming: American Journal of Science, v. 30, p. 172-188.
- Stevenson, R. E., 1956, Geology of the Bullhead quadrangle: South Dakota Geological Survey Geologic Quadrangle, 1 p.
- Taylor, O. J., 1965, Groundwater resources along the Cedar Creek Anticline in eastern Montana: Montana Bureau of Mines and Geology Memoir 40, 99 p.
- Terwindt, J. H. J., and Breusers, H. N. C., 1972, Experiments on the origin of flaser, lenticular and alternating sand-clay bedding: Sedimentology, v. 19, p. 85-98.
- Thom, W. T., and Dobbin, C. E., 1924, Stratigraphy of Cretaceous-Eocene transition beds in eastern Montana and the Dakotas: Geological Society of American Bulletin, v. 45, p. 481-505.
- Thomas, G. E., 1974, Lineament block tectonics--Williston-Blood Creek Basins: Bulletin of the American Association of Petroleum Geologists, v. 58, p. 1305-1322.
- Thompson, R. K., 1972, Functional morphology of the hindgut gland of Upogebia pugettensis (Crustacea, Thalassinidea) and its role in burrow construction: Ph.D. dissertation, University of California at Berkeley, 202 p.

- Todd, J. E., 1910, Preliminary report on the geology of the northwest-central portion of South Dakota in Report of the State Geologist for 1908: South Dakota Geological Survey Bulletin 4, p. 13-76, 193-207.
- Waage, K. M., 1961, The Fox Hills Formation in its type area, central South Dakota: Wyoming Geological Association Guidebook, 16th Annual Field Conference, p. 229-240.
- Waage, K. M., 1968, The type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota, Part 1. Stratigraphy and paleoenvironments: Peabody Museum of Natural History (Yale University) Bulletin 27, 175 p.
- Warne, J. E., and Stanton, R. J., Jr., 1971, Stop 2: Rockdale railroad cut: in Perkins, B. F., ed., Trace fossils, a field guide: Louisiana State University, School of Geoscience, Miscellaneous Publication 71-1, p. 11-15.
- Weimer, R. J., and Hoyt, J. H., 1964, Burrows of Callianassa major Say, geologic indicators of littoral and shallow neritic environments: Journal of Paleontology, v. 38, p. 761-767.
- Wilde, E., 1983, Stratigraphy and petrography of the Fox Hills Formation in the Baker and Wibaux 1:100,000 quadrangles, eastern Montana: M.S. Thesis, Montana School of Mines, Butte, Montana, 300 p.
- Williams, G. D., and Burk, C. F., Jr., 1966, Chapter 12, Upper Cretaceous, in McCrossan, R. G., and Glaister, R. P., eds., Geological history of western Canada: Calgary, Alberta, Alberta Society of Petroleum Geologists, p. 169-189.
- Winchester, D. E., Hares, C. J., Lloyd, E. R., and Parks, E. M., 1916, The lignite fields of northwestern South Dakota: United States Geological Survey Bulletin 627, 169 p.